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ÚSTAV ELEKTROENERGETIKY

SEMICONDUCTOR UTILIZATION FOR THE CAPTURE OF IONIZING RADIATION

VYUŽITÍ POLOVODIČŮ PRO ZÁCHYT IONIZAČNÍHO ZÁŘENÍ

BACHELOR'S THESIS
BAKALÁŘSKÁ PRÁCE

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2. Choose suitable materials for the direct conversion of ionizing radiation into electricity.
3. Assemble experimental nuclear cell and perform measurement.
4. Results and discussion.

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ABSTRAKT

Tato bakalářská práce popisuje typy a vlastnosti nukleárních článků a analyzuje vzájemné působení ionizujícího záření a polovodičů. Polovodičové nukleární články jsou stroje, které přeměňují energii ionizujícího záření na elektřinu, detektory využívají polovodičové materiály k měření veličin. Součástí tohoto projektu je popis ionizujícího záření, polovodičů, nukleárních článků a detektorů. Následně je popsán betavoltaický nukleární článek a jeho součásti. Je realizováno měření polovodičového nukleárního článku a je proveden rozbor potvrzující pravdivost teoretických poznatků.

KLÍČOVÁ SLOVA: Betavoltaika; Ionizační záření; Nukleární článek; Přímá přeměna energie; Radioaktivita; Detektor

ABSTRACT

This Bachelor's thesis describes the types and characteristics of nuclear cells and analyses the interaction between ionising radiation and semiconductors. Semiconductor nuclear cells convert the radiation energy into electricity, while detectors utilise the semiconductors for measurement. The thesis introduces the reader to ionizing radiation, semiconductors, describes the nuclear cells and detectors. Then the betavoltaic nuclear cell and its components are described. The measurement and its evaluation is realised to prove the concept of semiconductor nuclear cell.

KEY WORDS: Betavoltaics; Detector; Direct Energy Conversion; Ionizing Radiation; Nuclear cell; Radioactivity

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LIST OF SYMBOLS AND ABBREVIATIONS

RTG – Radioisotope Thermoelectric Generator

Symbol	Name	Unit
$\mathring{A}$	Radioactivity	Bq
B	v/c ratio	-
c	Speed of light	$m \cdot s^{-1}$
dE	Energy loss	eV
dx	Path increment	m
e	Elementary charge	eV
E	Particle energy	eV
E_{avg}	Average particle energy	eV
E_{eh}	Energy needed to create one e-h pair	eV
E_g	Bandgap width	eV
F_F	Fill factor	-
I	Mean excitation potential	eV
m_0	Electron ret mass	kg
N	Number density of atom	$kg \cdot m^{-3}$
N_0	Number of particles from source	-
N_β	Number of particles reaching the cell	-
P_{rad}	Radiated power	W
Q	Collection efficiency	-
r	Electron reflection probability	-
R_L	Load resistance	Ω
R_{sh}	Shunt resistance	Ω
R_S	Series resistance	Ω
$T_{1/2}$	Half-life	year
v	Velocity	$m \cdot s^{-1}$
V_0	Open circuit voltage	V
Z	Atomic number	-
η	Total efficiency	%
η_β	Radiation efficiency	%
η_c	Collection efficiency	%
η_{conv}	Conversion efficiency	%
η_s	Semiconductor efficiency	%

1 Introduction

In the last centuries, there was an extreme advancement in all the fields of scientific studies. Two of the most important discoveries were the existence of ionizing radiation and the discovery of semiconductors and their applications. There are many effects of the radiation force, both positive and negative ones. There is a big potential hidden inside the radioactive materials that humanity is trying to use to its benefit. This thesis combines the knowledge of ionizing radiation and semiconductors, describes their interaction mechanics and their possible applications.

This thesis first describes the individual types, applications and hazards of ionizing radiation. The semiconductor materials are introduced and their function mechanism is described. The thesis then explains the possible ways of how to convert the ionizing radiation into electricity, its effectiveness and practical applications. Further the semiconductor's ability to detect the radiation is presented. The first chapter also includes a brief history of radiation studies, nuclear cells and semiconductor materials.

In the next part of this thesis, the betavoltaic nuclear cell and its components are discussed. After describing the betavoltaic battery work principle, the radiation source and the converter are analysed. Then the materials available for further measuring are described.

Two laboratory measurements of the ionizing radiation and semiconductor interaction are performed as a practical part of the thesis. The first measurement was realised with the purpose of confirming the theory, the second one to confirm the first measurement's findings and to acquire more precise results. Both experiments are thoroughly described and their conclusions are presented.

In the following chapter, the measured results are calculated theoretically to evaluate whether the measuring was correct. The power radiated from the radiation source and theoretical cell power output is calculated. Then, the thesis estimates the penetration depth of the radiation in Silicon and Germanium. The evaluation of the findings is included at the end of the thesis.

2 IONIZING RADIATION AND SEMICONDUCTORS

This chapter introduces the reader to the theory behind the ionising radiation, semiconductor materials, nuclear cells and detector devices.

2.1 Ionizing radiation types and their applications

There are about 50 naturally occurring radioisotopes in nature and much more were created in laboratories. They have unstable nuclei that are decaying over time, emitting radiation. The most common forms of that radiation are alpha, beta and gamma radiation. The intensity of radiation decreases over time. It is characterized by the measure called half-life which is the time in which the half of the nuclei decays. The specific types and uses of radiation are described below.

The types of radiation can be divided in many ways. The most important division is done according to the fact whether the radiation is ionizing or non-ionizing. The ionizing radiation has enough energy to ionize other atoms, disrupting their chemical bonds. It can be divided into directly and indirectly ionizing radiation. Directly ionizing radiation consists of charged particles with enough kinetic energy, which after interacting with other atoms liberate their electrons primarily through the Coulomb force. Indirectly ionizing radiation carries chargeless particles. Another way to divide the radiation types is whether the radiation consists of particles (with their own mass) or electromagnetic radiation such as photons [1] [2].

2.1.1 Alpha radiation

Alpha radiation is a directly ionizing particle radiation. Alpha particle consists of two neutrons and two protons. It has very low penetrating abilities and carries the positive charge. The atom transmutes into another element when it alpha-decays. Alpha decay occurs in very heavy elements, such as uranium or thorium, with the nuclei containing many neutrons. The examples of alpha radiation sources are nuclides of ^{210}Po, ^{228}Th, ^{232}U, ^{239}Pu [3].

Alpha sources have a limited range and high specific ionization of particles. They are used in measuring physical quantities of gasses, their pressure or density. It can also be applied to measure the thickness, temperature or pressure of the thin layers and films. Another application, alpha-particle hydrometer was developed for measuring the humidity of air. Alpha radiation sources are also used in smoke detectors in ionization chambers. The ability of alpha radiation to ionize air finds various other applications. Thanks to its positive charge, alpha radiation is used to eliminate the static electric charge created among others by friction, which is a hazard in production processes, for example in textile production. The advantage of the nuclear static eliminators over the electric ones is that they cannot produce sparkling, therefore are safe in inflammable environments. Alpha sources are installed in lightning rods where positive ionization of air around it strongly attracts lightning. Alpha radiation sources are also used in positive ion generators in air conditioners [4] [5].

Alpha radiation is used in indirect conversion radioisotope power sources. They provide electrical power by converting heat which is generated by the decay of radioisotope fuel using thermocouples. Radioisotope Thermoelectric Generators, also called RTGs, include no moving parts and thanks to the long half-life of the fuel they are ideal power source for spacecraft. Thanks to the fact that alpha radiation particle carries a positive charge, its energy can be directly converted into electricity. Those sources are discussed later.

2.1.2 Beta radiation

Beta radiation is another directly ionizing particle radiation. When the atom beta decays, it emits a high-energy electron or positron. Electrons carry the electric charge e-, positrons carry a positive one e+. Beta particles are created in the nucleus which has too many protons or neutrons. In beta- decay, the neutron decays into the proton, electron and antineutrino. Beta+ decay involves a proton decaying into the neutron, positron and neutrino. There are no positron emitters in nature. The third type of beta decay is called electron capture, where electron in the inner shell of the atom combines with one of its protons, creating a neutron and emitting a neutrino. Beta radiation has higher penetrating properties than alpha, but much lower than gamma radiation. The pure beta radiation sources are ^{90}Sr, ^{147}Pm, ^{63}Ni or ^{3}H. Some beta radiation sources can decay in multiple pathways, creating different radioactive materials [6] [7].

Beta decay has various applications in medicine, including radionuclide therapy for curing cancer, medical tracers and detectors. Measuring the ^{14}C to ^{12}C concentration is used for carbon artefact dating, which calculates the age of objects by measuring their radioactivity. Beta radiation enables the thickness monitoring of materials. Beta decay is used in RTGs as well. This radiation can be directly converted into electricity, which will be discussed later.

2.1.3 Neutron radiation

Neutron radiation is indirectly ionizing particle radiation. It is the result of nuclear fusion, nuclear fission, spontaneous fission and other nuclear reactions. Neutrons emitted from such reactions have very high penetrating abilities. To absorb a high-energy neutron, it first has to be slowed down by a material with light nucleus, like hydrogen. Neutrons outside the nucleus are unstable and decay by beta decay. It means neutron radiation makes other materials radioactive, which requires the shielding to protect against the other types of radiation as well [8].

Neutron radiation is used on a large scale in nuclear reactors, where nuclear fission creates a controlled reaction producing large amounts of heat energy. The neutrons created by fission cause a chain reaction. The same process occurs during the atomic bomb explosion. Because of high risks and hazards of using neutrons as a compact power source, the neutron radiation is not a suitable energy source for nuclear cells and therefore for this thesis.

2.1.4 Gamma and X-ray radiation

Gamma and X-ray radiation is a high energy electromagnetic radiation. The radiation particles are photons with wavelengths ranging from 1 nm to 10 pm for X-ray and 10 pm to 1 pm for gamma photons. The photon is able to ionize the atom when its ionizing energy is higher than the energy necessary to remove the weakest electron from the atom. Gamma radiation often accompanies alpha and beta radiation. The typical sources of gamma radiation are ^{40}K, ^{137}Cs and ^{226}Am. Gamma and X-ray radiation carries no charge or static mass, but it can ionize matter indirectly using Photoelectric Effect (lower energy photon emission), Compton Scattering (photon transfers part of its energy to an atom) or Pair Production (high energy gamma particle produces an electron and hole or positron) [9] [10].

In medicine, gamma radiation is commonly used in radiotherapy, surgical knives, killing bacteria and sterilising the equipment thanks to its ability to kill living cells. Gamma sources are used as medical tracers, this radiation is used in crack and defect detection in materials like pipes and in aircrafts. Gamma radiation is also the effect of nuclear fission in nuclear reactors and atomic bomb explosion. X-rays are used in radiography, which is material scanning thanks to the fact that denser materials stop more X-rays. Other common applications are in medicine and painting scanning. Gamma radiation can be converted into electricity, which will be discussed later.

2.2 Semiconductor types and characteristics

The most commonly used semiconductors are monocrystalline semiconductors with diamond (Si, Ge) or zinc blende (compound semiconductors) crystalline lattice. The valence electron of the semiconductor material may break the covalent bond and become a free electron, leaving behind a hole. Both free electron and hole are available for conduction. Semiconductor materials have valence band and conduction band separated by a thin layer called bandgap.

Intrinsic semiconductors contain no impurities and foreign atoms in their crystalline structure. They contain the same number of electrons and holes and are very difficult to produce. Extrinsic semiconductors are doped by small amounts of impurities. This procedure is called doping and can be performed using several technological procedures. Depending on the added atoms the semiconductor becomes either the n-type or p-type. N-type semiconductors contain excess of electrons in the conduction band whereas the p-type semiconductor has additional holes in valence band. N-type semiconductors are doped with atoms that have more valence electrons than the semiconductor material, for example silicon with four valence electrons is doped with arsenic with five, so some electrons will not be a part of covalence bond, becoming the free electrons. Doping with atoms with less valence electrons create p-type semiconductors, where some electrons are missing the covalent bond and the hole is created.

In electric field, the charge carriers in the semiconductor are accelerated in a direction determined by the electric field orientation. This carrier transport type is called drift. Carriers move thanks to the diffusion as well, which is a quantum probability movement of the particles. Free electrons and holes are generated by lifting the electrons from the valence band into the conduction band to equal the numbers of electrons and holes. This can be achieved in various ways including thermal agitation, ionization, photon excitation or reversed biasing the semiconductor.

2.3 Ionizing radiation and semiconductor interaction

To generate the carriers in semiconductor, several methods may be applied. First of them is thermal generation in which the electrons are thermally excited to cross the bandgap. The lower the bandgap energy the easier it is for thermal excitation to happen. Electromagnetic radiation may also generate charge carriers. This effect is used in photovoltaics and photo detectors. By absorbing the photon, the electron excites and is lifted from the valence band into the conduction band. If the electron energy is higher than the bandgap, the electron moves toward the bandgap edges, leaving the hole behind. Carrier generation by charged particles works by momentum transfer from the particle to a valence electron of an atom. Only a part of the energy loss creates electron-hole pairs. For beta radiation to create a single electron-hole pair of energy E_g (bandgap energy) it takes ($2.8 \cdot E_g + 0.5$ eV) plus ($1.8 \cdot E_g$) lost to acoustic photon and 0.5 eV to optical photons (occurrence called Bremsstrahlung). This means, that the larger bandgap, the greater efficiency is possible to obtain. This is true for radiation energies that are large with respect to the bandgap.

Radiation types and energy transfer

- Visible and ultra violet light

In general, a single electron–hole pair will be produced by a photon. The photon will be absorbed close to the surface (typically a fraction of a micro meter in silicon).

- X-rays

  A “point” interaction with the production of many electron–hole pairs in a small spatial region is expected. The number of pairs can be estimated from the average energy necessary to create an electron–hole pair.

- α particles

Because of the high, strongly velocity-dependent ionization, the penetration depth is rather short (a few micro metres). The density of electron–hole pairs increases with path length as the velocity decreases and has a pronounced maximum at the stopping point of the particle.

- β radiation

Due to the much lower mass of electrons with respect to a helium nucleus and the factor-of-two lower charge, β radiation ionizes much more feebly than α radiation. β radiation will therefore penetrate deeply into the semiconductor, or even pass through it, producing roughly uniform electron–hole pair densities along its path so long as the velocity remains relativistic and producing increased density at the end of its path. A relativistic singly charged particle is often referred to as minimum-ionizing particle.

- High-energy charged particles

This type of radiation will penetrate the semiconductor with nearly constant velocity, producing uniform electron–hole density along its path. The density is nearly independent of the particle energy and is proportional to the square of the charge of the ionizing particle.

- Nonrelativistic charged particles

Such as protons and nuclei will produce an ionization density inversely proportional to their energy (which decreases with path length) and proportional to the square of their charge. Simultaneous measurement of the energy loss in a thin detector and of the total energy can therefore be used for particle identification.

- Other types of radiation

Such as neutrons and very high-energy photons, may also produce signals in semiconductors, for example by recoiling a silicon nucleus or creating electron–positron pairs that are capable of producing electron–hole pairs by ionization. The probability for this to happen is so small, however, that semiconductors by themselves are inappropriate for neutron and high-energy photon detection. However, interleaving semiconductors with other materials, which converts this radiation into something detectable, is possible.

2.4 Nuclear cells

Nuclear cells are the devices that transform nuclear energy into electricity. They can be divided into two main categories: thermal energy converters and non-thermal converters. Possible power cell types are presented in Figure 2.1 [11] [12] [13].

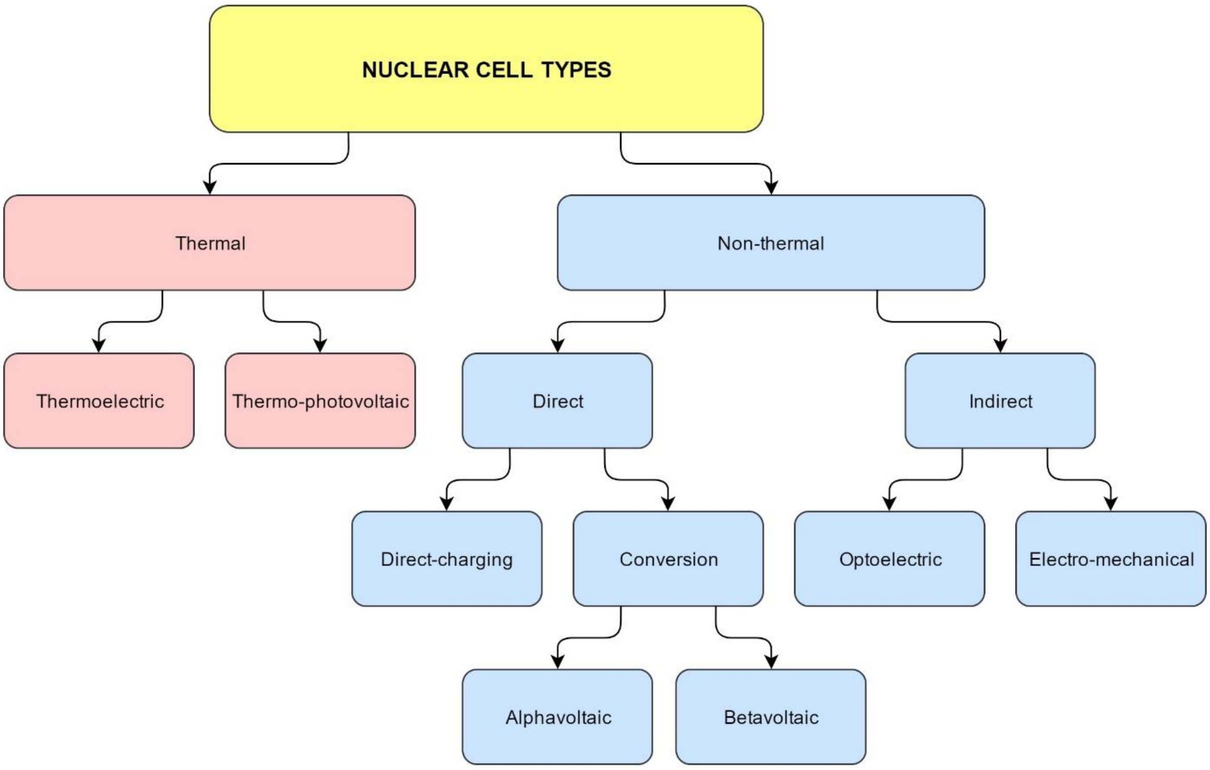


Figure 2.1 Nuclear cell types

Non-thermal energy converters are energy converters without energy transforming into thermal energy. Specific types of nuclear cells are described below along with evaluation whether the specific type is suitable for wider usage and for this thesis realisation.

- Direct charging battery

The idea behind Direct Charging Battery, as shown at Figure 2.2 [14], is that the radioactive material emitting alpha or beta radiation is placed inside or near one plate of the capacitor, charging it negatively when using beta emitter or positively when using alpha source. Between the plates of the capacitor (of any shape), where the output voltage of the battery appears, is placed dielectric material or vacuum. Direct Charging Batteries produce very high voltages (up to hundreds of kilovolts) with extremely small currents [nA]. There is also a special kind of direct charging battery powered by gamma radiation by using Compton scatter. Although Direct Charging Battery is easy to build, its low effectiveness, high voltages and low currents make it unsuitable for the practical part of this thesis [15].

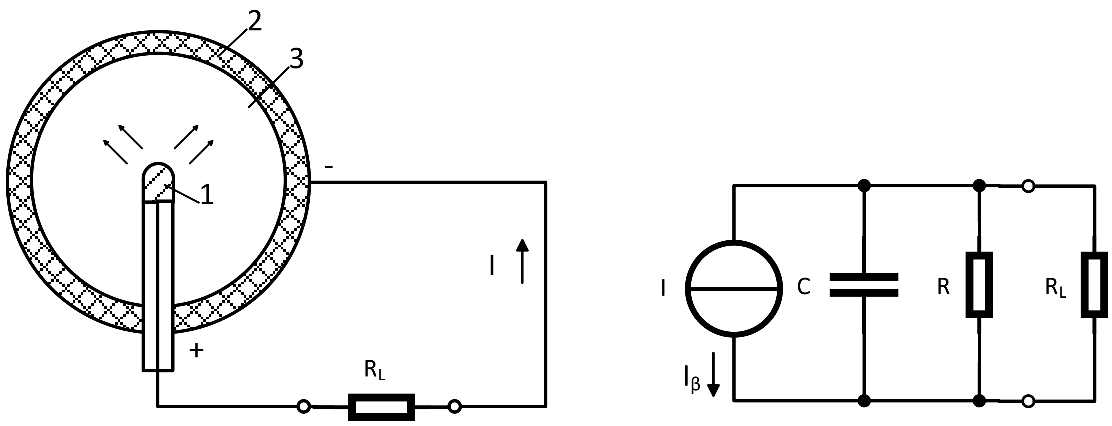


Figure 2.2 Direct charging battery (left) and its equivalent circuit (right). The radiation emitted from source (1) passes through the vacuum (3) into collector plate (2), where negative charge appears.

- Direct conversion battery

Direct Conversion Batteries use alpha and beta radiation interaction with semiconductor´s p-n junction. The alpha or beta particle creates electron-hole pairs while traveling through the semiconductor (see Figure 2.3). A proper radioactive source as well as semiconductor material must be chosen to assure the radiation interaction with the p-n junction. Alphavoltaic batteries are only laboratory experiments, mostly because of destructive tendencies of alpha radiation. Betavoltaic batteries are currently available on the market, being able to assure a low-power and long-term energy source [16]. Betavoltaic power source is proposed later in this thesis and is thoroughly described later [17].

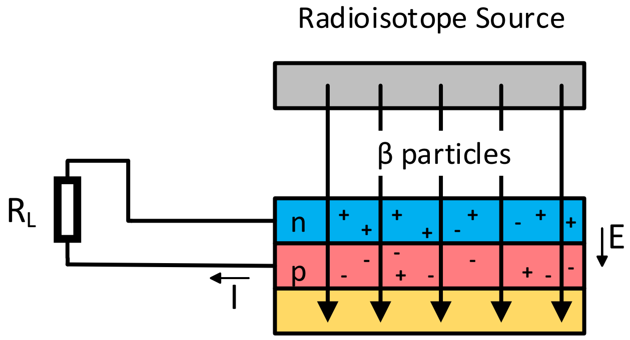


Figure 2.3 Betavoltaic battery design

- Indirect conversion battery

Indirect Conversion Batteries first convert the radiation into different type of energy which is later converted into electricity. The form of energy between conversions can vary depending on the technology used. Using light as the energy between conversions, Optoelectric Battery uses alpha or beta radiation particles inside radio-luminescent material to produce light. The radio-luminescent material is surrounded by photodiodes or photovoltaic cells which create electric energy from light (see Figure 2.4) [18]. Mechanical energy is utilized in Reciprocating Electromechanical Atomic Batteries that use the charge between two electrode plates to bend them towards each other. As the plates touch, they discharge and pull apart again. The piezoelectric material in plates creates electric current from mechanical movement. Because of specific material requirements this type of battery will not be realised as part of this thesis.

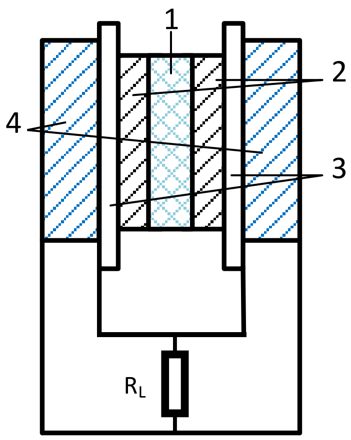


Figure 2.4 Optoelectric battery design. The radiation is emitted from (1), converted into visible photon radiation in (2), passing through optic material (3) into photovoltaic material (4)

- Thermal conversion generator

Thermal conversion power cell converts radioactive energy from fuel into heat. The heat is then converted in Thermal Conversion Generator into electricity. Radioisotope Thermoelectric Generator uses thermocouplers for that conversion. Thermocoupler is a device that uses difference of temperatures to create electric current using thermoelectricity phenomenon. Radioisotope Thermophotovoltaic Generator utilizes thermophotovoltaic cells to generate current. Because of high energy of the radiation requirements and high temperature differences required for proper function of this type of source, Thermal Conversion Generator will not be utilized in this thesis.

2.5 Detectors

Particle detector is a device that is used to detect, tracks or identify particles. Detectors also measure particle’s attributes such as charge, momentum or spin [19]. The detectors are commonly used in nuclear physics, particle physics, medicine and environmental supervision. They are utilized in radiation protection systems as detectors. The types of radiation detectors are described below.

2.5.1 Detector types

- Gaseous ionization detectors

In gaseous ionisation detector, the ionized particle passes through the sensor filled with gas. A particle then ionises a gas molecule and the ions cause the current to flow between the plates of the chamber. The basic types of gaseous ionisation detectors are ionisation chamber, where a single particle creates a single ion-particle pair, proportional counter, where a particle creates an electron-ion pair that causes an avalanche of ionised atoms and Geiger-Müller tube, where the process creates multiple avalanches.

- Semiconductor detectors

In semiconductor detectors, the electron-hole pairs are created by particle leaving part of their energy while traveling through the semiconductor. Number of the electrons is transferred from the valence band into conduction band, resulting in current spikes on electrodes attached to the semiconductor. Silicon or germanium semiconductors are the most commonly used [20] [21].

- Cherenkov detector

Cherenkov radiation is emitted when a particle or radiation travels through the material at the speed greater than the speed of light inside that material. The wavelength of the photon may vary depending on the material particle speed and its type. The detectors use this to calculate the velocity of the known particles, their quantity and the direction they travel.

- Scintillation counter

Scintillation effect uses scintillator material that emits visible light after it absorbs the energy of the radiation. Depending on the material, the photons are emitted with varying delay. After the scintillator, there is a photo-multimeter tube that converts light into electrical pulses. It is possible to estimate the initial energy of the particle by measuring intensity of the flash.

- Dosimeters

Dosimeters are devices used for personal protection or medical and industrial processes that measure radiation doses. They often have more than one function and work on varying principles, depending on the dosimeter used. MOSFET dosimeters, most often used in medical dosimeters and radiotherapy use very small MOSFET with oxide attached to its gate. Radiation causes defects in oxide, which simulate electron-hole pairs in the transistor. Thermo-luminescent dosimeters emit light after radiation exposure. Another type of dosimeter is a film badge dosimeters and quartz fibre dosimeter. Electroscopes are devices used for detecting the presence of electric charge in objects but some types are also used in radiation detectors.

2.5.2 Function requirements

Particle detectors are classified depending on their reliability, precision and usability. Detector must be resistant against the background noises of different types. Radiation background consists of thermal and blackbody radiations from the surrounding environment, internal background causes noise interference from within the detector like dark currents, density fluctuations, current noise and others. Signal background is the ability to detect the slightest change in the steady signal while distinguishing it from the noise. Each detector has a sensitive area, which is an area over which the detector responds to the radiation. The larger the area, the more universal the detector is and the larger is the scale of its use.

2.5.3 Semiconductor detectors

Semiconductor detectors are currently being used in large variety of fields including particle, nuclear, optical and x-ray physics, astronomy, material testing and medicine. This type of detectors use low-noise low-power electronics for signal reading. The main advantages of semiconductor detectors are their superiority over the other types of detectors in the precision, integration possibilities and their readout options. Amplifier systems are added to semiconductor detector circuits to further enhance their precision. The research of semiconductor detectors also develops other fields of study. The most important material properties for the semiconductor detector could be summed into the following:

- The small band gap leads to a large number of charge carriers per unit energy loss of the ionizing particles to be detected. The average energy for creating an electron–hole pair is an order of magnitude smaller than the ionization energy of gases.
- The high density ($2.33\ g\cdot cm^{-3}$) leads to a large energy loss per traversed length of the ionizing particle ($3.8\ MeV\cdot cm^{-1}$ for a minimum ionizing particle). Therefore, it is possible to build thin detectors that still produce large enough signals to be measured. In addition, the very small range of δ-electrons prevents large shifts of the centre of gravity of the primary ionization from

the position of the track. This is why an extremely precise position measurement (of a few μm) is possible.

- Despite of the high material density, electrons and holes can move almost freely in the semiconductor. The mobility of electrons (1450 $cm^2 \cdot V^{-1} \cdot s^{-1}$) and holes (450 $cm^2 \cdot V^{-1} \cdot s^{-1}$) is at room temperature only moderately influenced by doping, which is this case is the number of charge carriers in the semiconductor. Therefore, charge can be rapidly collected and detectors can be used in high-rate environments.
- The excellent mechanical rigidity allows the construction of self-supporting structures.

2.6 History of ionizing radiation and semiconductors

The whole new chapter in human history began in 1895 when Wilhelm Röntgen discovered X-rays. His discovery was followed by Henri Becquerel, who in 1896 researched uranium salts and discovered radioactivity that was described by Marie Curie Skłodowska. She also constructed the first mobile X-ray machines utilized in World War I. The first research of radiation exposure was made after the "Radium Girls case", where watch painting using radium ink poisoned an unknown number of workers. After that, the radiation exposure became a public topic and first safety protocols for working with radioactive materials were created. During the World War II nuclear fission was weaponized and the atomic bomb was created. After Hiroshima and Nagasaki bombings many people discovered first-hand the destructive force of atomic power and many more were exposed and poisoned by radiation. After the war, nuclear reactors with controlled fission reaction were build and utilised for electricity production.

The first documented observation of the semiconducting effect was made by Michael Faraday in 1833. In following years, the focus on semiconductors was because of their two properties, rectification of metal-semiconductor junction and sensitivity to light. The research in that field led to invention of radar, microwaves. In 1839 Alexander Edmund Becquerel discovered the photovoltaic effect [22]. In 1929, Walter Shottky experimentally confirmed the presence of the barrier in metal-semiconductor junction. The transistor was invented by John Bardeen, Walter Brattain and William Shockley at Bell Labs in 1947. Shockley then left Bell Labs and opened Shockley Semiconductor Laboratory of Beckman Instruments [23]. He searched for the brightest students in universities to build new company. It is said that Shockley brought silicon to Silicon Valley. A part of the company left after Shockley decided to discontinue the research into silicon-based semiconductors. They created a new company called Fairchild Semiconductor Company, which is the root company for Intel, AMD and other world semiconductor giants.

In 1953, Paul Rappaport described the first betavoltaic device with efficiency of 0.2 %. This device utilised SR^{90}-Y^{90} radiation source and degraded due to radiation damage. Dr Larry Olsen and his team at Donald W. Douglas Laboratories developed the first working nuclear battery for heart pacemakers with power output of 400 μW called Betacel battery which exhibited the efficiency of 8% in later development and was used in pacemakers for over 100 people. Betacel used ^{147}Pm as a radiation source. Olsen then published "Review of Betavoltaic Energy Conversion" where he suggested suitable beta radiation sources for betavoltaic batteries. In 2010, City Labs got the general license to sell Nano-Tritium battery, the only betavoltaic battery available for commercial sale. Nano-Tritium betavoltaic batteries are available in three configurations, 0.8 V, 1.6 V and 2.4 V open circuit voltage with 50-350 nA maximum current. They have official operating temperature range from -40 ºC to 80 ºC. City Labs company employees the pioneer of betavoltaic research Larry Olsen, PhD, as well as other top tier scientists in nuclear cell science.

Several other companies have specific licenses, being able to sell betavoltaic batteries to customers with specific training [24] [25].

In 1961, Radioisotope Thermoelectric Generator developed by Atomic Energy Commission was first used in the spacecraft. RTG used ^{238}Pt radioactive fuel which, thanks to its half-life of 88 years, provides a long-lasting power source. RTG and its later forms were utilised in numerous space missions. Long distance missions of Voyager I and II were powered by Multi-Hundred Watt RTG with power output 158 W operational for 30 years. Viking I and II were powered by 42.6 W RTG, Pathfinder mission to Mars was equipped with four massive generators, each housing 14 RTGs with power output of 1 kW. Curiosity mission used Multi-Mission RTG for Mars exploration mission which contained 4.8 kg of plutonium dioxide, providing 2000 W of thermal power which was converted into 110 W of electrical power thanks to low temperatures in space [26].

3 NUCLEAR CELL PROPOSAL

This chapter describes the components of betavoltaic batteries. It discusses their aspects and their possible material and usability. Later, the betavoltaic nuclear cell will be designed with application of available components.

3.1 General proposal

The typical betavoltaic power source is composed of a radiation source, a converter that converts radiation energy into electricity and an electrical circuit, which enables the electricity measuring and application. Betavoltaic battery also usually includes shielding from radiation, mechanical protection and may include filters between the radiation source and converter to stop unwanted particles. Its strongest advantages are long lasting power output depending on half-life of the radiation source chosen and degradation speed of the betavoltaic and its ability to operate in wide temperature ranges from -50 ºC to 150 ºC.

In general, betavoltaic cells work mechanism is very similar to widely known photovoltaic one. Photovoltaic cells produce electrical power while a photon with specific wavelength hits the surface covered with semiconductor material of the cell. The energy of the photon creates an electron-hole pair, which creates a potential difference on the electrodes of the semiconductor. Betavoltaic cell works on the same principle, using the energy of electrons instead of photons. Each electron is able to create thousands of electron-hole pairs, where on the other hand the photons have enough energy only to create one [27].

The equivalent circuit of the betavoltaic battery is shown in Figure 3.1. The R_{sh} is the shunt resistance, which corresponds with the carrier recombination-generation in depletion region. R_S represents the series resistance relevant to the diode neutral regions and contacts, R_L is the load resistance.

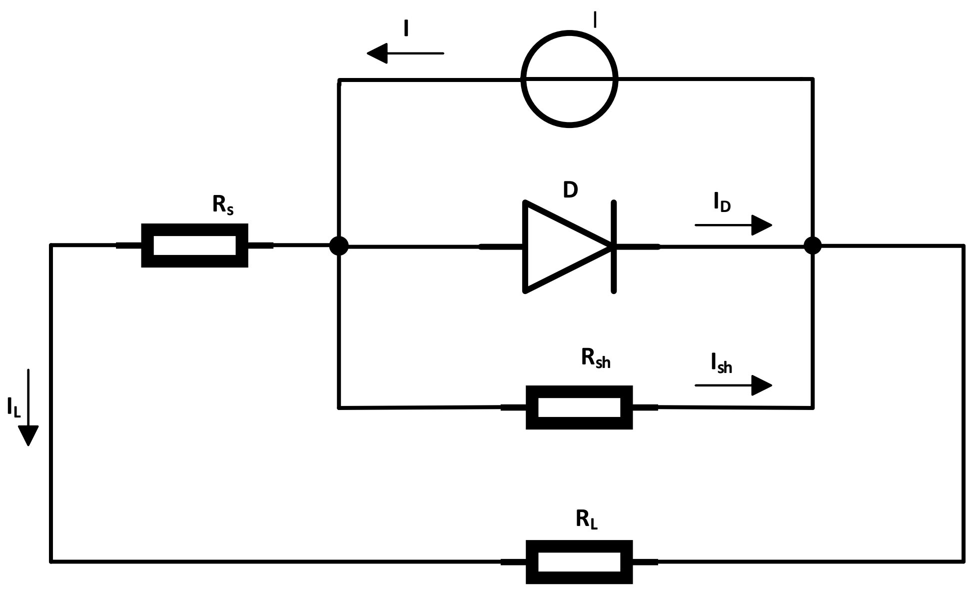


Figure 3.1 Betavoltaic substitute diagram

3.1.1 Radiation source

To choose the proper radiation source for the power cell, the material must meet the following requirements:

- The half-life of the isotope must be long enough to keep its radiation strength for the sufficient period of time.
- The high specific power of the isotope is required. Specific power describes how much Watts of energy is produced from one gram of the isotope.
- The specific activity must be high enough to create sufficient amount of radioactive decay reactions.
- The higher is the decay energy, which is the amount of energy emitted from an isotope during its lifetime, the better. It is calculated from the mass difference of the particle before and after the radioactive decay.
- When considering beta particles, the radiated electrons must have low energy not to displace the atom of the semiconductor, which is about 300 keV. The damages semiconductor has lower bandgap width, which leads to higher losses during electron-hole generation.
- The isotope should be a pure beta emitter, which means it radiates only beta radiation if possible. The result particle of the decay cannot be radioactive, or at least should radiate only beta particles with tolerable energy of the electrons.
- The isotope must be available in sufficient amounts to realise the power source.
- The isotope must be contained in a stable compound.
- The undecayed isotope must be used, which is the isotope whose atoms did not undergo the decay process yet.

The requirements above are met only by a small number of isotopes. Table 1 compares the most significant ones which are later discussed individually [28].

Table 1 Isotope specifications and parameters

Parameter	Isotope				
	Tritium	Nickel-63	Promethium-147	Strontium-90	Krypton-85
	^{3}H	^{63}Ni	^{147}Pm	^{90}Sr	^{85}Kr
Half-life $T_{1/2}$ [year]	12.32	100.1	2.62	28.9	10.56
Decays into	Helium-3	63-Copper	Samarium-147	Yttrium-90	Rubidium-85
Max energy [keV]	18	67	225	540	687
Avg. energy [keV]	5.7	17.4	62	198	251

According to Larry Olsen, tritium is considered the most suitable energy source for betavoltaic power sources. It is a pure beta emitter, its half-life is long enough to sustain the desired power output. Tritium decays into helion, which is a non-radioactive isotope of helium. It also has low energy of decay so the electrons are easily absorbed in the semiconductor. Tritium is a gas that combines with oxygen, creating T_2O which is tritium water. The specific activity of tritium is about $358 \cdot 10^{12}$ Bq·g^{-1}, of T_2O it equals $268 \cdot 10^{12}$ Bq·g^{-1}. It can be stored as a solid tritide material using metals like titanium or scandium. Tritium is commonly used as a radiation source in betavoltaic power sources [29].

Nickel-63 is another pure beta emitter with low electron energy. It decays into stable copper-63 and its only available compound is $NiCl_2$. Its half-life is about 100 years, which enables the long-term use of this isotope as a power source with very low power output. Nickel-63 is often used in laboratory-made betavoltaic devices.

Promethium-147 is the third suitable power source for betavoltaic batteries. ^{147}Pm is a pure beta emitter. It has only 2.62 years of half-life, its energy of electrons is significantly higher than the one of tritium and nickel. On the other hand, it can produce higher power outputs than the previous isotopes.

Strontium-90 is a pure beta emitter with higher decayed electron energy values. It has specific activity of $5.21 \cdot 10^{12}$ $Bq \cdot g^{-1}$, decays into yttrium-90, which is a radioactive isotope which undergoes beta decay with 2.28 MeV maximum energy of the decayed electrons. Strontium-90 and yttrium-90 may cause material degradation of the semiconductor because of the high energies of electrons radiated. ^{90}Sr was used in the first betavoltaic battery created by Paul Rapport in 1953 [30].

Krypton-85 is the isotope currently available for this project. It has maximum energy of decayed electrons little higher than strontium-90, but it is not a pure beta emitter. ^{85}Kr also decays via gamma decay with the energy of 518 keV. Its decay product is rubidium-85, which is a stable isotope. Krypton-85 is not suitable for commercial use thanks to its gamma decay, but it is possible to use it in laboratory measuring which is the part of this bachelor thesis [31].

3.1.2 Converter

A converter is a semiconductor that absorbs the energy of the electrons from the source by creating electron-hole pairs. The typical semiconductor consists of two electrodes, space charge region, p-doped region and n-doped region as showed in Figure 3.2 [32]. The electrons passing through the p-doped region leave part of their energy in the material, creating electron-hole pairs. Freed electrons travel to the space charge region, creating positive charge on the electrode of the semiconductor. For the pair created in n-doped region, this mechanism works inversely. The electrons created in depleted region recombine, causing current to flow. This process is shown on Figure 3.3 [33].

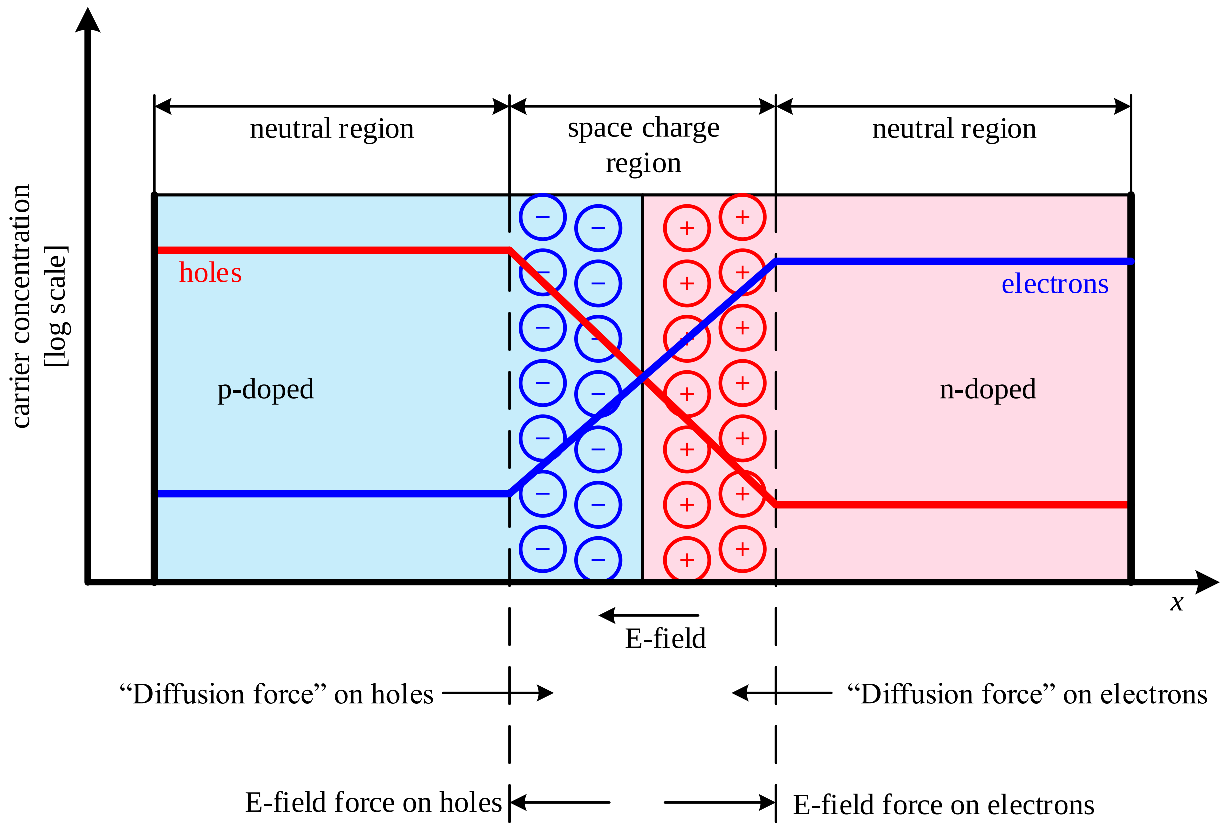


Figure 3.2 P-n junction [32]

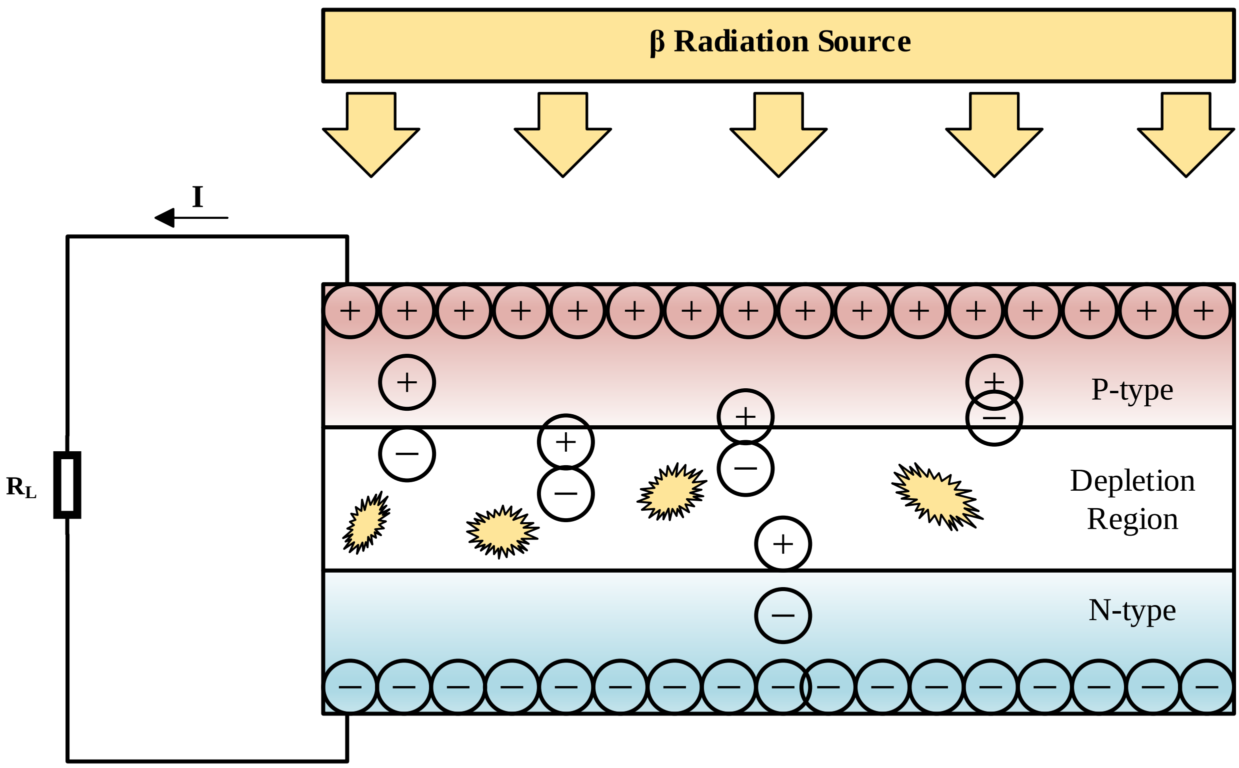
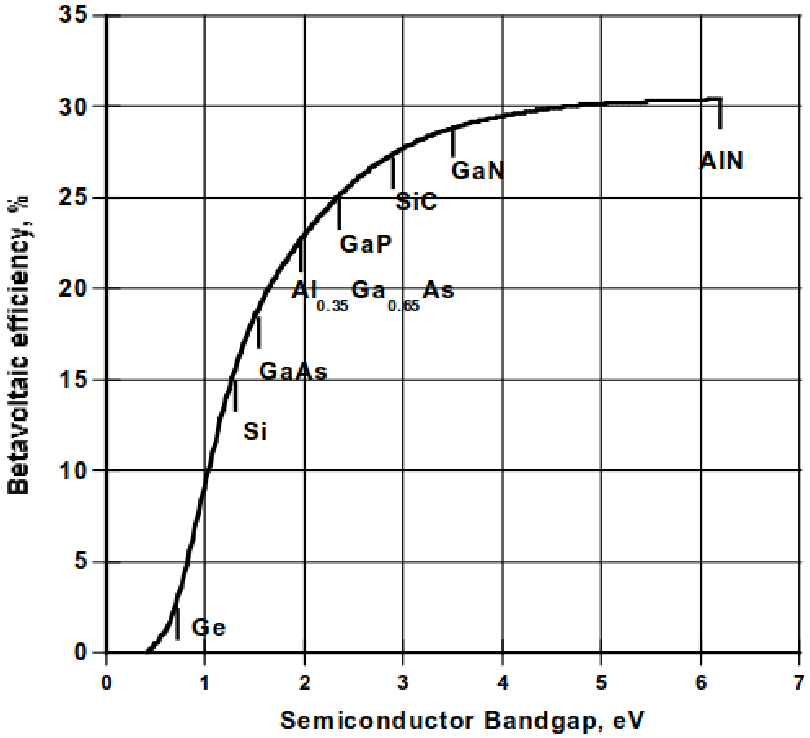


Figure 3.3 Betavoltaic battery inner process [33]

The theoretical efficiency of the betavoltaic cells depending on the bandgap width is shown in Figure 3.4. The theoretical efficiency decreases over time with material degradation caused by defects in the semiconductor crystal caused by high energy beta particles. The power output decreases as well. The rate of material degradation of betavoltaic caused by radiation depends mostly on two factors, the intensity of irradiation and the strength of bond in semiconductor. Using the betavoltaic with GaN material increases the stability and lifetime of the power cell [34].



3.4 Maximum betavoltaic efficiency depending on the bandgap width [34]

Depending on the material of the semiconductor, the specific wavelengths of radiation can be converted. For betavoltaic applications, the semiconductors with III-V compounds like gallium arsenide or gallium phosphide are usually chosen. Although they have smaller bandgaps, it is possible to fabricate them as crystalline films. In SiC junction bandgaps are bigger, but it is difficult to produce large enough silicon carbide semiconductors without defects that cause significant dark currents in the material. GaN materials have the suitable properties, which is why they are often chosen as the proper betavoltaic.

3.1.3 Electrical circuit and shielding

For its small power output, the betavoltaic batteries are usually connected directly to load. In case of higher voltage outputs and low current outputs, the protection circuit with the transformer must be applied. This is rarely required, mostly because the betavoltaic cells are custom made for the purpose they will serve.

Depending on the radiation source used, varying shielding strengths are required. For low energy pure beta radiation source like Tritium, only thin layer of shielding material is required. The shielding requirements increase with increasing energy of beta radiation. Much stronger shielding is required while the source with partial gamma radiation, like Krypton-85, is utilised. In such cases, most of the nuclear cell’s volume and weight are radiation shields.

3.2 Available option

For practical simulation, Krypton-85 is available. This isotope radiates beta particles with 687 keV maximum energy in 99.56 % of the decays. 0.434 % of the decays produce a gamma particle with 518 keV maximum energy and the rest are lower energy beta and gamma particles. Krypton-85´s specific power is 0.517 $W \cdot g^{-1}$, with radiated power of $3.22 \cdot 10^{-10}$ $W \cdot Ci^{-1}$. Krypton-85 is naturally a gas, which can be incorporated into solid material by fission recoil, high energy bombardment of the solid surface by high energy Krypton-85 ions, diffusion into crystals, crystallization of solids from melts and adsorption onto outgassed surfaces [35].

As a second radiation source, Americium-241 is available. Americium-241 is an alpha radiation source with average particle energy of 5.638 MeV.

To calculate the overall efficiency η, the thin foil of beta radiation source is considered for one-dimensional geometry for our analysis. The overall efficiency can be written as a product of three efficiencies, shown in Equation 3.1 [36].

$$\eta = \eta_\beta \cdot \eta_c \cdot \eta_s \ (-) \tag{3.1}$$

where

$$\eta_\beta = \frac{N_\beta}{N_0} \ (-) \tag{3.2}$$

is the ratio of the ratio of beta particles that reach the semiconductor to the ones emitted from the source,

$$\eta_c = (1 - r) \cdot Q \ (-) \tag{3.3}$$

is the coupling efficiency, given by the product of absorption probability of beta particle with r being the probability of the electron reflection from the surface (-) and the collection efficiency Q (-) of electron-hole pairs and

$$\eta_s = e \cdot V_0 \cdot \frac{F_F}{E_{eh}} \ (-) \tag{3.4}$$

is the semiconductor efficiency, where e is the elementary voltage (eV), V_0 is the open circuit voltage (V), F_F is the fill factor of the VA characteristics and E_{eh} is the energy needed to create one electron-hole pair in the semiconductor (eV).

4 MEASUREMENT REALISATION AND EVALUATION

This chapter of the thesis describes and evaluates the realised measuring. The goal of the measuring was to detect the effects of the ionizing radiation on the semiconductor material. The measurement was realised twice, first to check for any detectable effect and the second to confirm the initial measurement's results and to document the results using more precise measuring instruments. The achieved results are later discussed.

4.1 First measurement

The purpose of the first measurement was to detect initially, whether the ionizing radiation has the effect on the semiconductor materials described in previous chapters. The experiment took place in the radiation laboratory of the Faculty of Electrical Engineering and Communications on Monday, March 13 at 2 PM. The laboratory was intensively lit through a window. The temperature in the room was 21.1 ºC with atmospheric pressure of 1020.6 hPa. Before the measurement could begin, several safety precautions had to be done. First, the shielding housing made of lead blocks was built to protect the measurement participants from the radiation [see Figure 4.1]. Every participant had to follow the instructions of the laboratory safety protocol. While being near the radiation source, protective glasses and gloves had to be worn.

Figure 4.1 Housing made of lead blocks

The measurement setup is shown in Figure 4.2, where the design of the measurement and real configuration is displayed. The protective housing (1) covers the radiation source holder (2) from all sides. Directly in front of the radiation source holder is the area for semiconductor cell placement (4). It needs to be directly in front of the source to maximise the amount of radiation passing through the semiconductor. In the back, there is a dosimeter (4) placed to detect the radiation intensity for the protective and informative meanings.

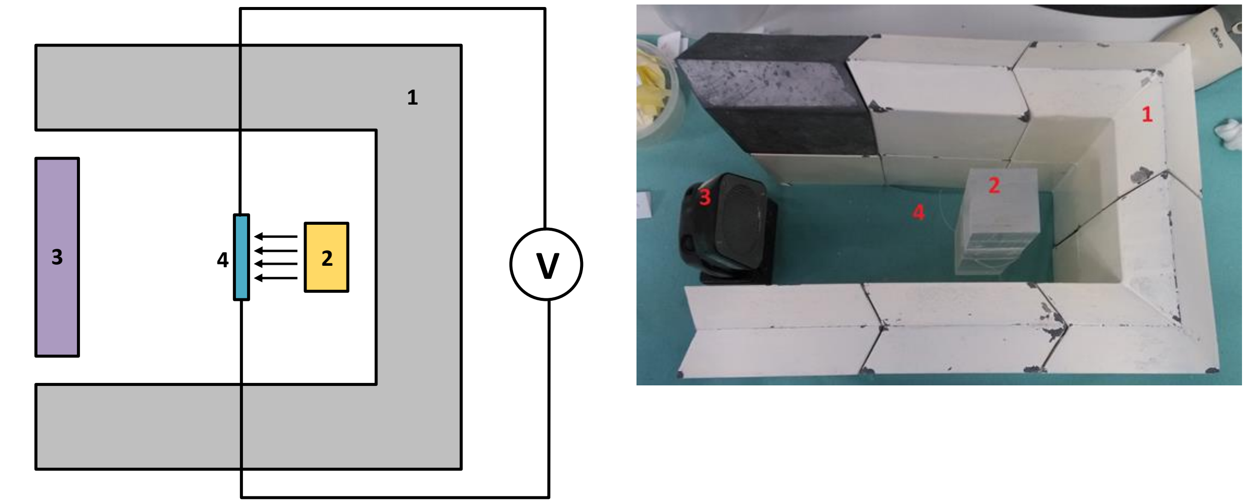


Figure 4.2 Experiment setup design (left) and realisation (right)

In the first part of the experiment the Kryptoon-85 with the activity of 10 MBq was used (see Figure 4.3 left). While being placed in the holder (2), the dosimeter (see Figure 4.3 rightT) displayed the activity of 42.2 kcps, which equals 42.2 kBq. The setup shows, that the dosimeter distant approximately 20 cm from the source detected only 0.42 % of the radiation emitted by the radiation source. This is caused mostly by small detecting area of the device and limited penetrating abilities of the radiation. While being one centimetre from the source, the dosimeter displayed the dose of 55 mSv.

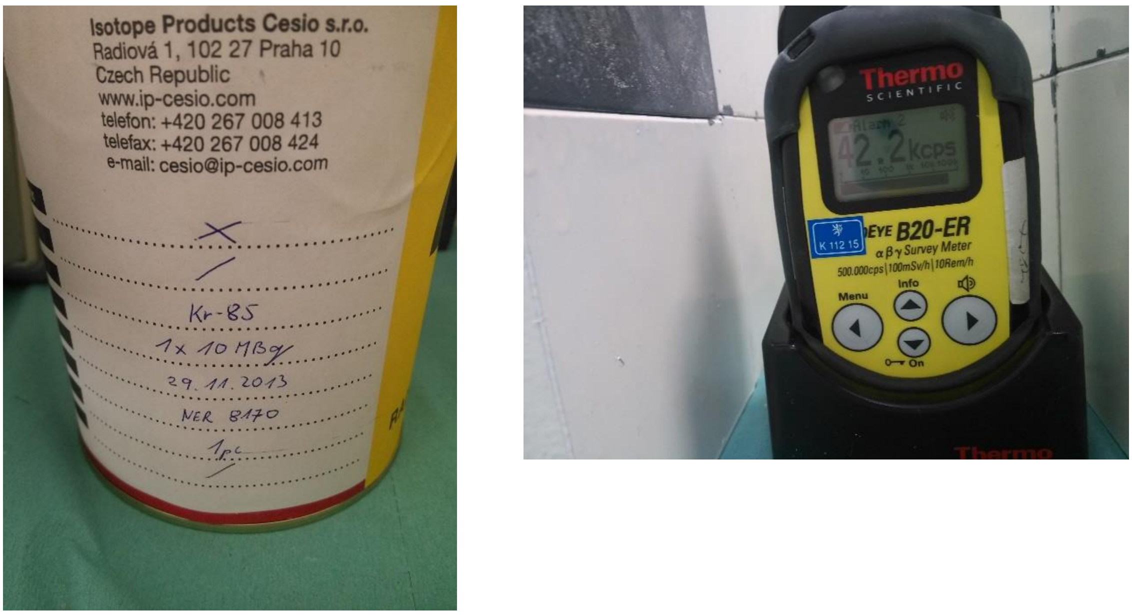


Figure 4.3 Krypton-85 container (left) and dosimeter with displayed count measurement (right)

After the experiment setup was ready, several devices able to interact with ionising radiation were prepared. Each device's electrodes were connected to the voltmeter (see Figure 4.4) during the measurement to detect the changes of their voltage output.

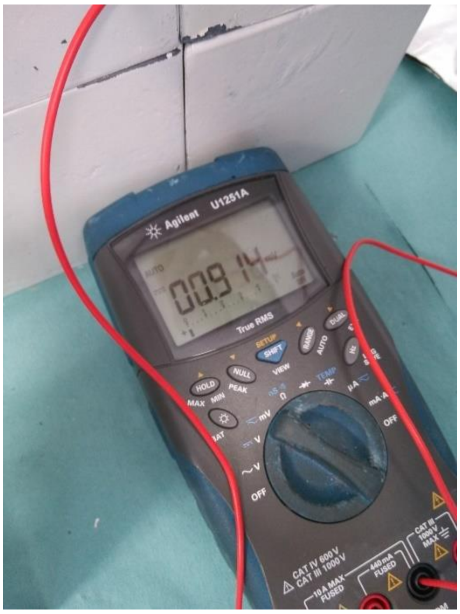


Figure 4.4 Voltmeter with measured voltage

The first measured device was a power semiconductor (see Figure 4.5). The object was placed directly in front of the radiation source, maximising the number of electrons which go through the active area of the semiconductor. Since the device was significantly used and damaged, there was no voltage detected on the voltmeter.

Figure 4.5 Power semiconductor

The next tested device was a coil with 1500 threads (see Figure 4.6). Although the stream of electrons from the radiation passes directly through the coil, there was no voltage detected on the voltmeter. This was caused by small charge of the electrons and their high velocity. In case the electrons were significantly slowed down, it would be theoretically possible to obtain some positive results.

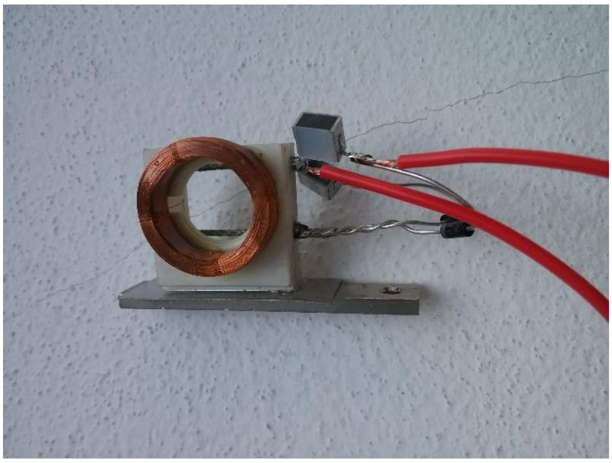


Figure 4.6 Coil with 1500 threads

Afterwards, the PIN diode was measured (see Figure 4.7). There was a small voltage detected in the diode before it was exposed to the radiation. The voltage was caused by dark currents, thermal noise and light noise in the inner structure of the diode. After the PIN diode was exposed to the radiation, no significant change occurred. The inner voltage remained unchanged. The radiation energy and intensity was not strong enough to open the diode. The semiconductor area inside the PIN diode was too small. Additionally, the diode was shielded with protective layer which blocked large portion of the radiation.

Figure 4.7 PIN diode

The following tested device was a monocrystalline solar cell (see Figure 4.8). The cell was first measured while being covered with aluminium foil which did not show any results. The foil efficiently shielded the beta particles and probably caused short circuit between the electrodes. The foil was removed and the significant voltage appeared on the electrodes of the monocrystalline solar cell without exposing it to the radiation. The room was strongly lit from the windows, which caused the solar cell to produce power. After the cell was exposed to the radiation source, the voltage dropped significantly. This unexpected result was the subject of further discussion and is evaluated below.

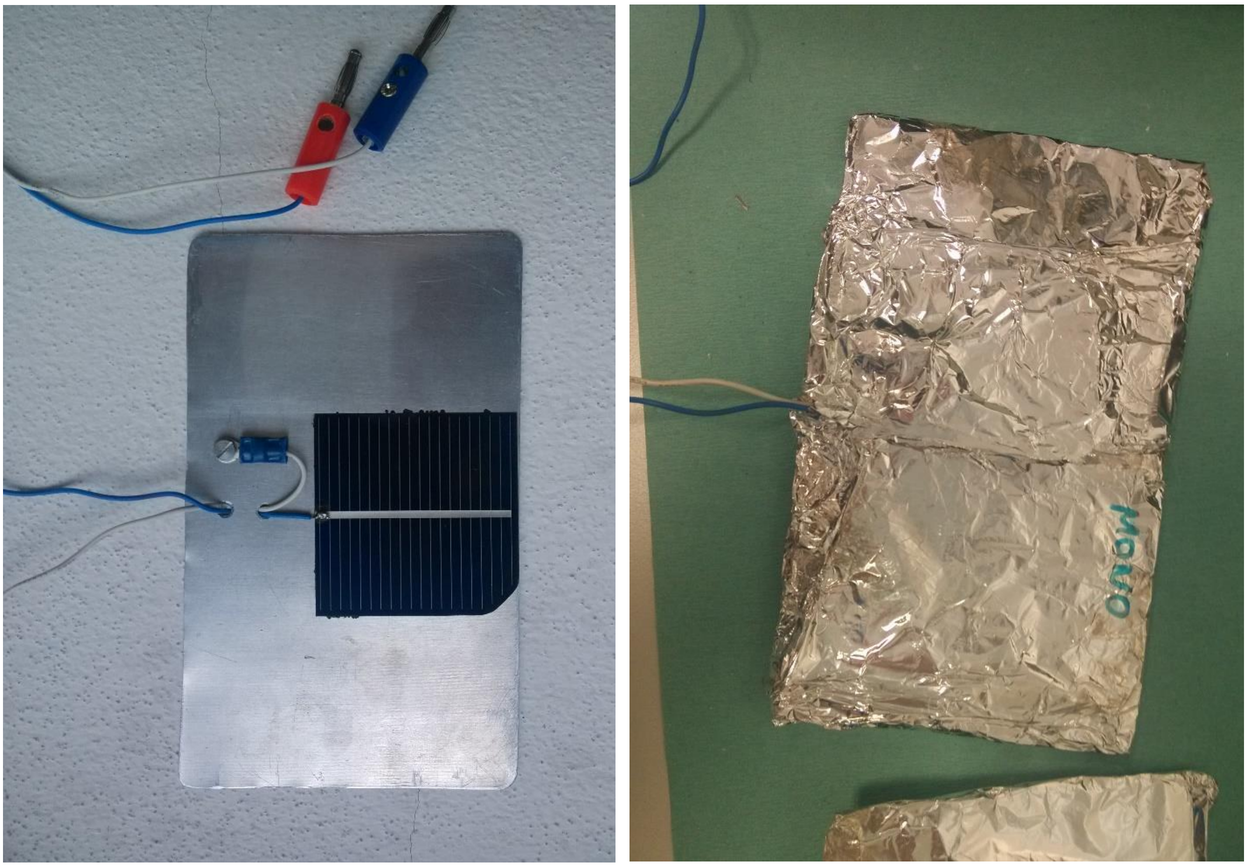


Figure 4.8 Monocrystalline solar cell naked (left) and covered with foil (right)

Next, the polycrystalline solar cell was tested (see Figure 4.9) the same way as the previous one. The first test with aluminium foil did not show any results. After removing the foil, the voltage of the cell appeared on the voltmeter. It was significantly lower due to the damage of the cell caused by cutting the crystal. Nevertheless, after exposing the crystal to the radiation source, the voltage dropped as well.

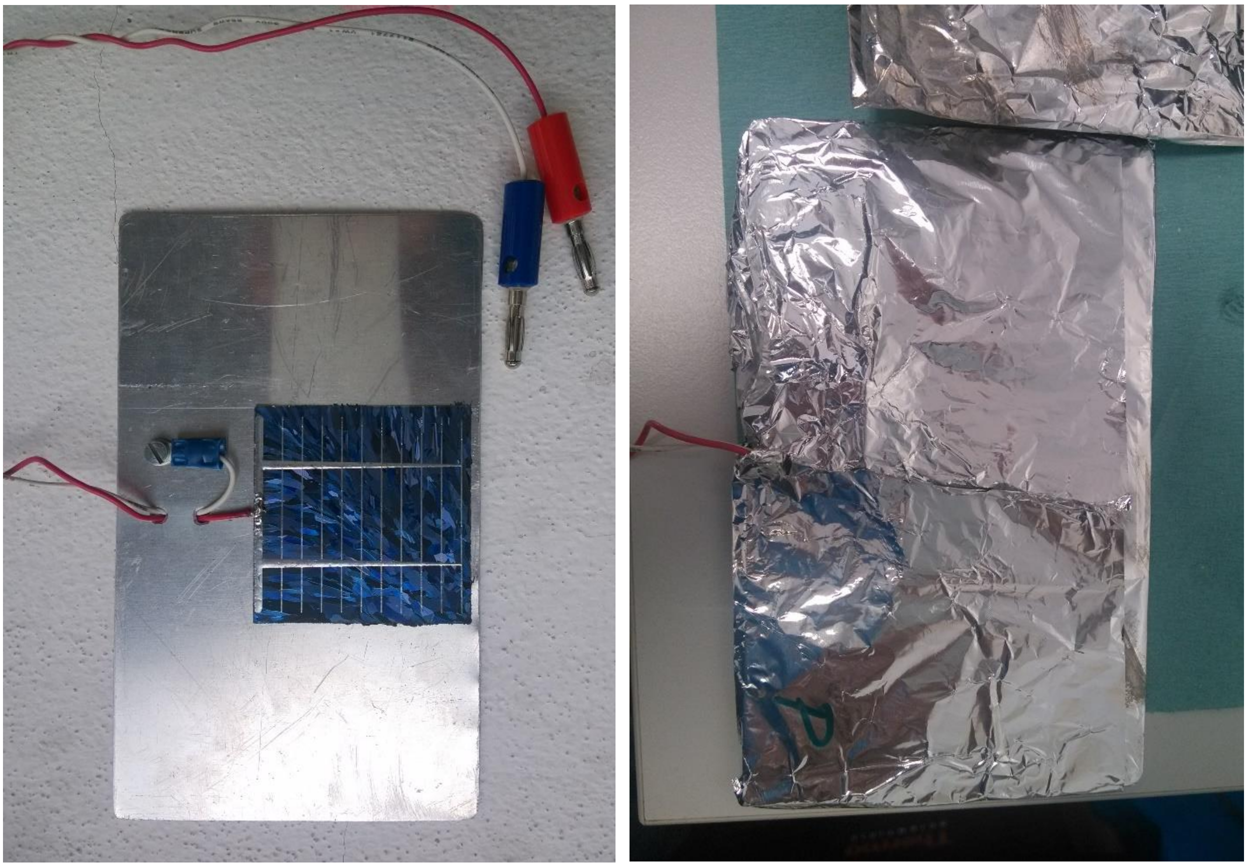


Figure 4.9 Polycrystalline solar cell naked (left) and covered with foil (right)

The last measurement included the amorphous solar cell (see Figure 4.10). The measurement with the aluminium foil did not show any positive results. Measurement without the foil showed the same results, as the one with the monocrystalline and polycrystalline cells. The initial voltage was higher than the voltage of the polycrystalline cell, but significantly lower than the voltage measured with monocrystalline one. The voltage drop was the least significant of all solar cells.

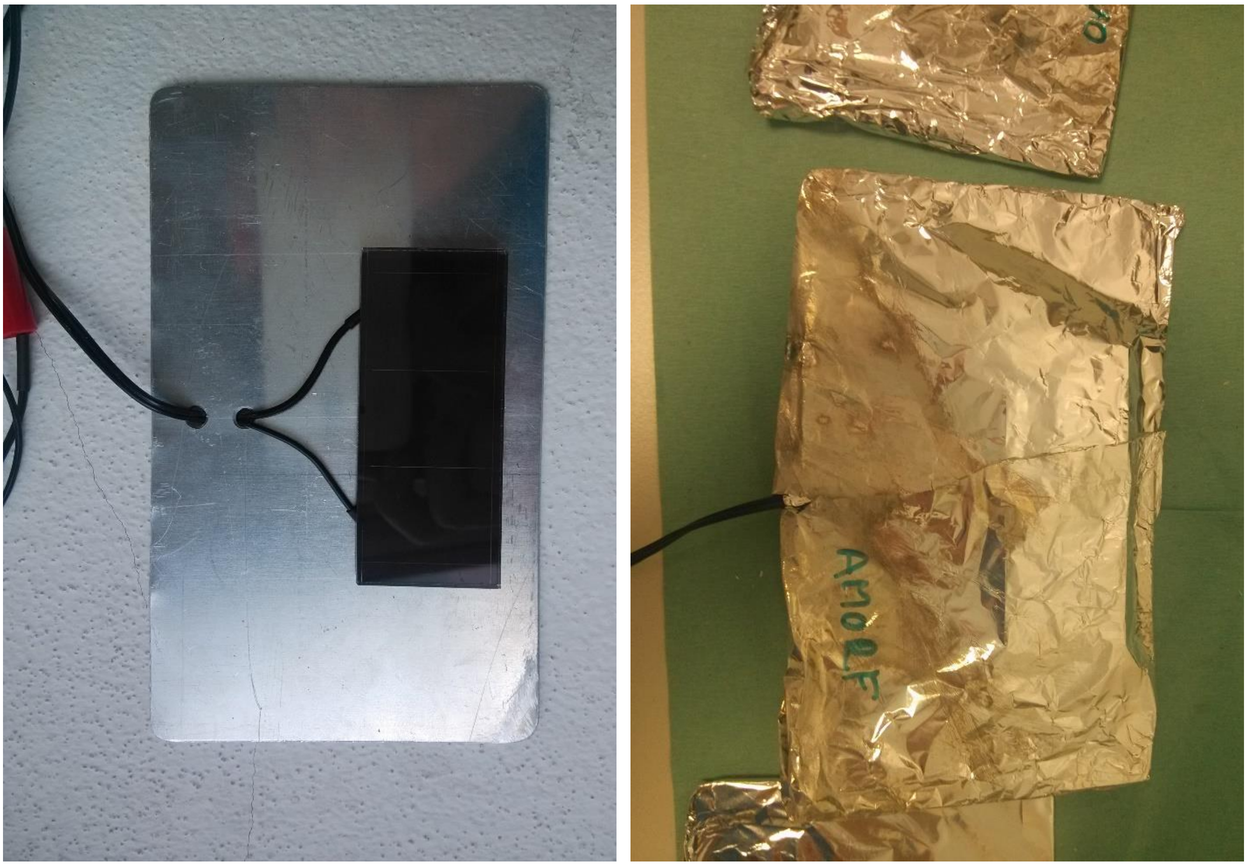


Figure 4.10 Amorphous solar cell naked (left) and covered in foil (right)

The measurement was repeated using Americium-241 alpha radiation source with 1 MBq activity. The dosimeter showed only insignificant radiation values. Alpha radiation has very low penetrating abilities and can reach only several centimetres in air. The power semiconductor, coil and PIN diode did not show any kind of interaction with the radiation, while monocrystalline, polycrystalline and amorphous solar cells interacted the same way with the alpha radiation as with beta.

The results of the laboratory measurement were unexpected, but promising. Although the first tested objects did not show any detectable voltage change, all three solar cells showed the same result. After researching the possible causes of this effect, the most probable explanation is the creation of the new recombination centres in the semiconductor. Radiation, while passing through the semiconductor, creates large number of electron-hole pairs, which in large concentrations are not pulled fast enough apart. Instead of travelling to the depletion zone and electrodes, resulting in producing the output current, the carriers created by the radiation particle as well as the original ones recombine in large numbers, shortening the carrier life and reducing the voltage output. To confirm the measurement results, the repeated measurement with more precise measuring devices was organised. For the devices used in the first measurement, see Table 2.

Table 2 First measurement devices

Device name	Type	Serial number
Voltmeter	Agilent U1251A	Private device
Dosimeter	RadEye B20-ER	724756541

4.2 Second measurement

The second measurement took place on Thursday, May 4 at 1 PM. The laboratory was moderately lit through a window. The temperature in the room was 21.5 ºC with atmospheric pressure of 1015.3 hPa. Its purpose was to evaluate whether the first measurement of this thesis was done correctly and to improve its accuracy. Instead of voltmeter, the digital multimeter was used to detect the voltage. Otherwise, only a few changes were made in comparison to the first testing. The protective measures were taken to ensure the measurement safety. The radioactive material used was the same one as in measurement one. The following objects were measured, while being exposed first to Krypton-85 and then to Americium-241: PIN diode (Object num. 1), thermoelectric generator (Object num. 2), monocrystalline solar cell (Object num. 3), monocrystalline solar cell with optical concentrator unit (Object num. 4), polycrystalline solar cell (Object num. 5) and amorphous solar cell (Object num. 6). All were first measured while being covered with black tape to isolate the cells from the light (see Figure 4.11, Figure 4.12, Figure 4.13). The tape disables the short circuit events which were present during the previous measurement. All measured objects were put directly in front of the radiation source, minimising the distance which the ionizing radiation travelled through air.

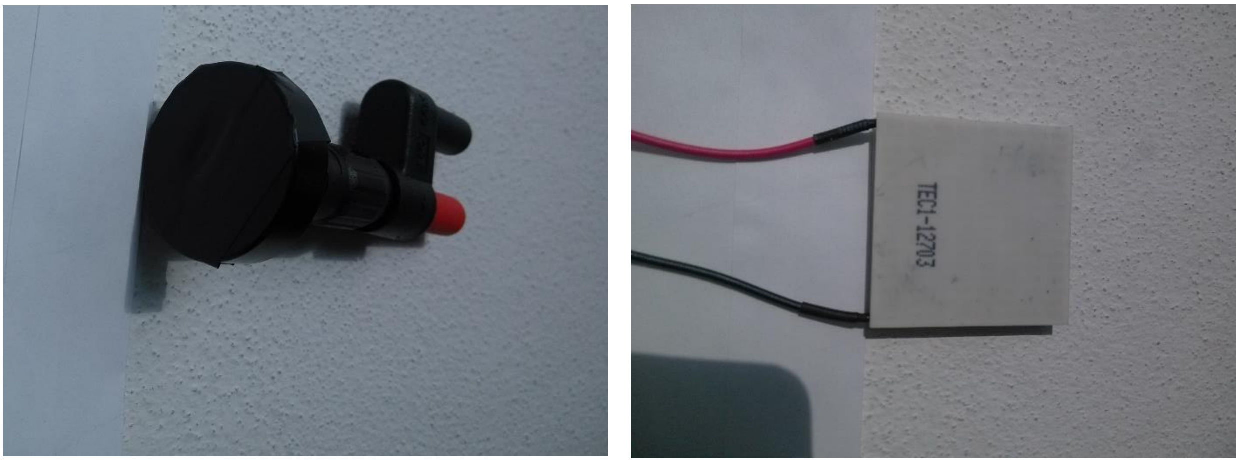


Figure 4.11 PIN diode (Object num. 1) cover in tape (left) and thermoelectric generator (Object num. 2) (right)

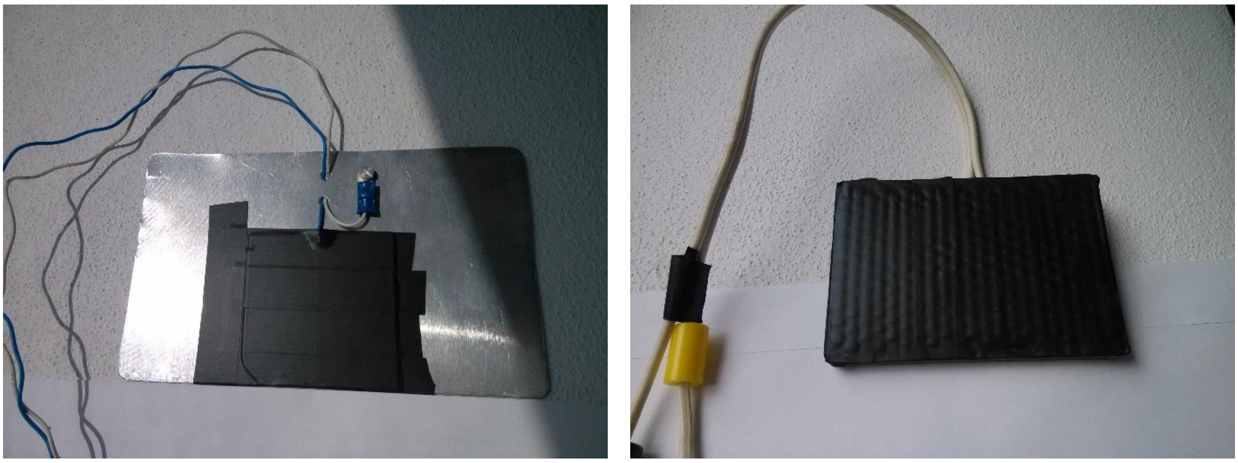


Figure 4.12 Monocrystalline solar cell (Object num. 3) in tape (left) and monocrystalline solar cell with optical concentrator unit (Object num. 4) in tape (right)

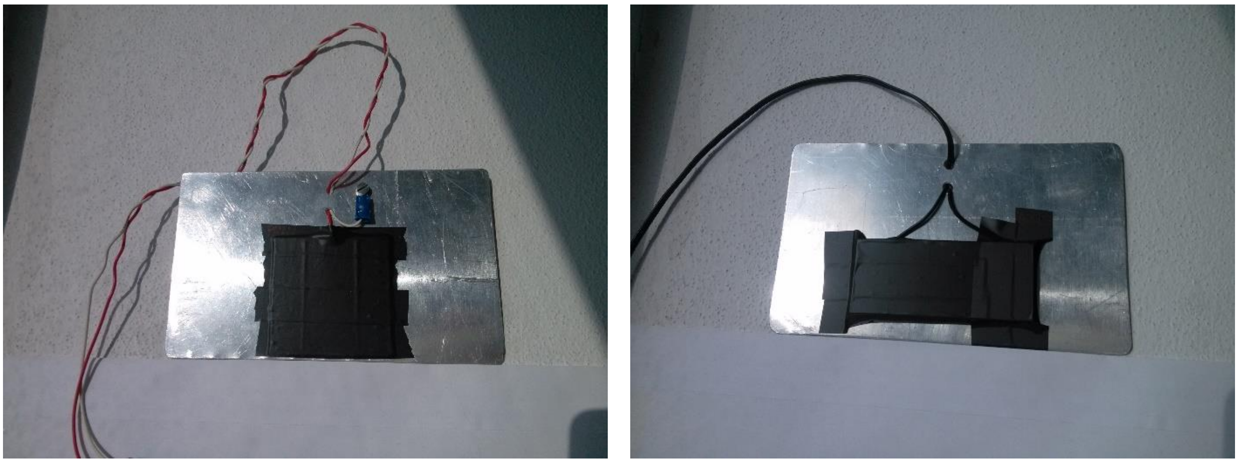


Figure 4.13 Polycrystalline solar cell (Object num. 5) in foil (left) and amorphous solar cell (Object num. 6) in foil (right)

The measured results with taped objects are shown in Table 3.

Table 3 Measurement with tape results

Measurement with tape	Measured voltage [mV]		
Measured object num.	No exposure	Krypton-85	Americium-241
1	0	0	0
2	0.5	0.5	0.5
3	22	22	25
4	12	11.5	12.3
5	0	0	0
6	0.8	0.8	0.6

The measurement concludes that no detectable change of voltage occurred in any of the measured objects after exposing it to the ionizing radiation. This could be explained either by the lack of interaction between ionizing radiation with the semiconductor materials, insufficient amount of radiation energy for large enough charge creation, or by tape blocking all radiation from entering the semiconductor material.

To eliminate the third option, the measured objects were stripped off and measured again, this time while using a hard paper box to block the light from entering the cells and thus creating charge in the semiconductor. The measured values in most materials were significantly varying, depending on the efficiency of blocking the sunlight.

The PIN diode (Object num. 1) changed its voltage output slightly, depending on the light intensity. The exposure to radiation had no visible effects. Thermoelectric generator (Object num. 2) produced increasing voltage over time while being exposed to the sunlight that heated it up. It showed no reaction to ionizing radiation exposure. Monocrystalline power cell (Object num. 3) changed its voltage output significantly, depending on the light intensity. The drop of voltage while being exposed to ionizing radiation was caused only by decrease of light the cell was exposed to. The same conclusion has been made about monocrystalline solar cell with optical concentrator unit (Object num. 4), polycrystalline solar cell (Object num. 5) and amorphous solar cell (Object num. 6).

The second measurement disproved the claims of the first experiment. The drop of voltage measured in the first measurement was caused only by decreasing the exposure of the cells to the sunlight. The measured semiconductor objects did not show any visible interaction with alpha and beta radiation of Krypton-85 and Americium-241. These measurement results do not agree with theoretical data from the previous chapters. For the measuring devices used in measurement see Table 4.

Table 4 Second measurement devices

Device name	Type	Serial number
Multimeter	Rigol DM3061	DM3D134900262
Dosimeter	RadEye B20-ER	724756541

5 Outcome analysis

This chapter of the thesis analyses the results of the previous measurements (see Chapter 4). The power output of the radiation sources as well as the output of the semiconductor nuclear cells is calculated. Then, the penetrating abilities of the ionizing radiation are simulated and discussed. At the end of the chapter the results of the thesis are presented.

5.1 Power output calculation

The power outputs of nuclear cells using the same radiation sources are calculated to compare them with the measurement's results. In this chapter, the equations used to calculate the power output and efficiency of the cell differ from the ones in Chapter 3. This is due to the lack of available information about the semiconductor materials. To calculate the possible voltage gained from the cell, the power radiated by the ionizing radiation source must first be obtained. That is possible to calculate from known average energy of the emitted particle and the activity of the source (see Equation 5.1).

$$P_{rad} = \text{Å} \cdot e \cdot E_{avg} \ \text{[W]}$$

(5.1)

$$P_{Kr} = 10 \cdot 10^3 \cdot 1.602 \cdot 10^{-19} \cdot 251 \cdot 10^3 = 4.02 \cdot 10^{-7}\ W$$

where $\mathring{A}$ is radioactivity of the source [Bq], e is the elementary charge [W] and E_{avg} is average energy of the particle [eV].

Next, the energy passing through the semiconductor can be approximated by analysing the shape of the radiation source and semiconductor proximity. Since the radiation source was coin-shaped and the cell was directly in front of the source, it is safe to assume that 45 % of the radiation passes through the semiconductor. For a single electron-hole pair with the energy of E_g to be created, the electron of beta radiation loses ($2.8 \cdot E_g + 0.5$ eV) of its energy, with additional ($1.8 \cdot E_g + 0.5$ eV) lose in photon generation. Bandgap width of Silicon is 1.3 eV. The efficiency of the conversion can be calculated from Equation 4.2.

$$\eta_{conv} = \frac{E_g}{2.8 \cdot E_g + 0.5 + 1.8 \cdot E_g + 0.5} \cdot 100\ [\%]$$

(5.2)

$$\eta_{Si} = \frac{1.3}{2.8 \cdot 1.3 + 0.5 + 1.8 \cdot 1.3 + 0.5} \cdot 100 = 22.89\ \%$$

The Krypton-85 has an average electron energy of 251 keV, radioactivity of the source was 10 MBq. The calculated radiated power output is $4.02 \cdot 10^{-7}$ W (from Equation 5.1). After taking the radiation loss and converter efficiency of 22.89 % (Silicon, from Equation 5.2) into consideration, the measured nuclear cell power output in the perfect semiconductor material would be $4.14 \cdot 10^{-8}$ W. The approximated efficiency of the system from calculated conversion efficiency (5.1) and radiation capture rate is 10.3 %, which is practically impossible. The realistic calculation [37] shows the maximum betavoltaic efficiency to be significantly less, depending on the source and converter choice. There are significant loses in semiconductor materials caused by carrier recombination speed and additional internal loses, which the equation did not account for. Additionally, part of the electrons of the beta radiation is reflected by the semiconductor surface.

The Americium-241 has an average electron energy of 5.638 MeV. Radioactivity of the sample was 1 MBq. The calculated radiated power output is $9.03 \cdot 10^{-7}$ W (from Equation 5.1). Since the alpha radiation consists of heavy particles, it is unwise to assume the conversion efficiency above. The experimental calculation [38] assume the maximum alphavoltaic efficiency to be 2.1 %. This would return the power output of $8.533 \cdot 10^{-7}$ W.

Considering the photovoltaic cells used during the measurement in the laboratory had power outputs in magnitudes of milliwatts, the power sources were much too weak for the measured voltage to show any visible change.

While making the reverse calculations, the 1 μW of electric power is assumed to be obtained. Considering the calculated maximum beta efficiency to be 10,3 %, the necessary radioactivity of the Krypton-85 to produce 1 V of voltage with 1 μA current would equal 241.4 MBq (from Equation 5.1). While calculating with alphavoltaic efficiency of 2.1 %, the Americium-241 would require the radioactivity of 117.15 MBq (from Equation 5.1) to produce 1 V of voltage and 1 μA current. These calculations ignore the power loss in air, power loss in semiconductor and other aspects, which further limit the conversion method.

5.2 Stopping range of the material

As explained above, the beta radiation loses its energy along its path while travelling through the semiconductor in approximately constant speed. For semiconductor to absorb the whole energy of the beta radiation, its thickness must be big enough to "stop" the electron while travelling through the semiconductor material. The following chapter of the thesis evaluates the thickness requirements.

The Bethe-Bloch formula is a mathematical equation, which estimated the energy loss per distance travelled of the particle through the material. While calculating with beta radiation energy loss, the initial formula must be adjusted to take the photon creation (Bremsstrahlung) into account [39]. The adjusted Bethe-Bloch formula is shown in the Equation 5.3.

$$-\frac{dE}{dx} = \frac{4 \cdot \pi \cdot e^4}{m_0 \cdot v^2} \cdot N \cdot Z \cdot \left[\ln\left(\frac{m_0 \cdot v^2 \cdot E}{2 \cdot I^2 \cdot (1 - B^2)} \right) - \ln(2) \cdot \left(2 \cdot \sqrt{1 - B^2} - 1 + B^2 \right) + 1 - B^2 + \frac{1}{8} \cdot \left(1 - \sqrt{1 - B^2} \right)^2 \right] \tag{5.3}$$

where -dE [eV] is the energy loss, *dx* [m] is the path increment, *v* [m·s^{-1}] is the velocity of the particle *c* [m·s^{-1}] is the speed of light, m_0 [kg] is the electron rest mass, *e* [eV] is the elementary charge, *N* [kg·m^{-3}] is the number density od absorber atoms, *Z* [-] is the atomic number of absorber atoms, *E* [eV] is the energy of the particle, *I* [eV] is the mean excitation potential and *B* [-] is the *v/c* ratio.

Using ESTAR software simulation [40], the stopping power of the Silicon and Germanium was calculated depending on the electron's energy. The simulation calculates with collision stopping power which is a result of the Coulomb collisions that result in the ionization and excitation of atoms and radiative stopping power which is the average rate of energy loss per unit path length due to collisions with atoms and atomic electrons in which Bremsstrahlung photons are emitted.

The software returns the graph of the stopping power value depending on the energy of the particle. The stopping power of the Silicon and Germanium is shown in in Figure 5.1 and

Figure 5.2. The stopping power from the simulation must be divided by the density of the material to acquire the energy loss increment value.

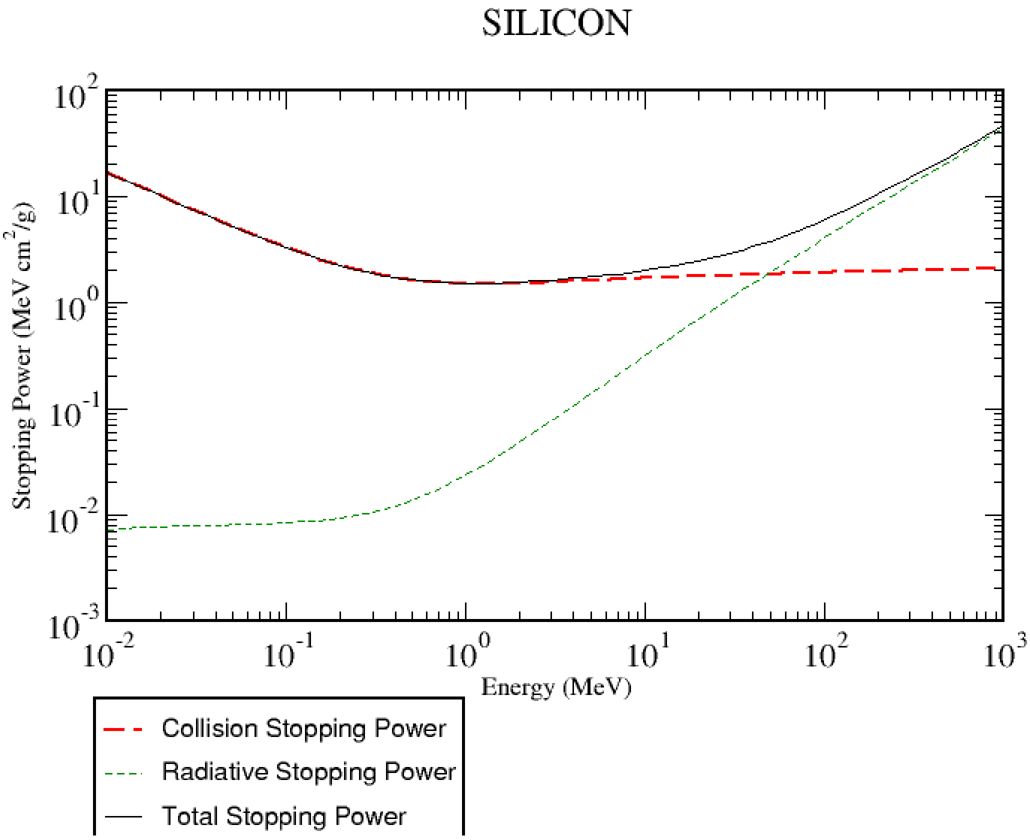


Figure 5.1 Silicon stopping power

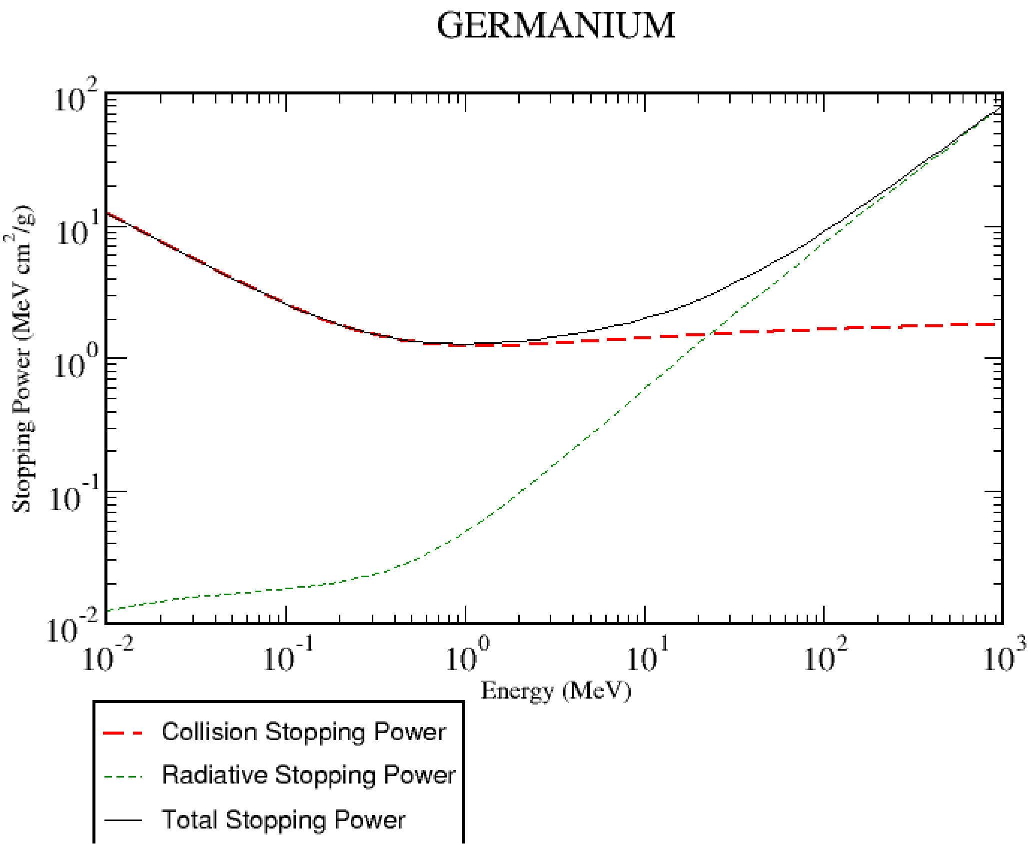


Figure 5.2 Germanium stopping power

The ESTAR simulation is also able to calculate the value of electron penetration depth. The values of Silicon and Germanium penetration depth depending on the beta radiation energy are shown in Figure 5.3 and Figure 5.4.

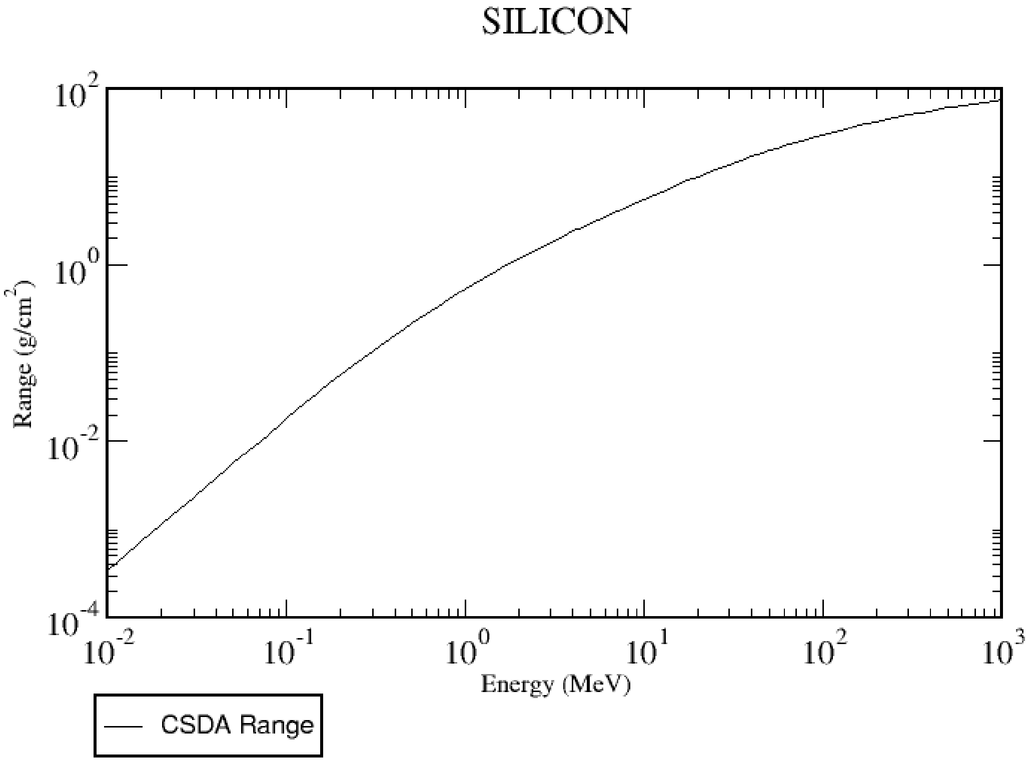


Figure 5.3 Beta penetration depth in Silicon

The density of Silicon is 2.329 g·cm^{-3}. Considering the maximum energy of Krypton-85 radiation of 687 keV, the Si semiconductor must be 1.288 mm thick to “stop“ the radiation and absorb its energy.

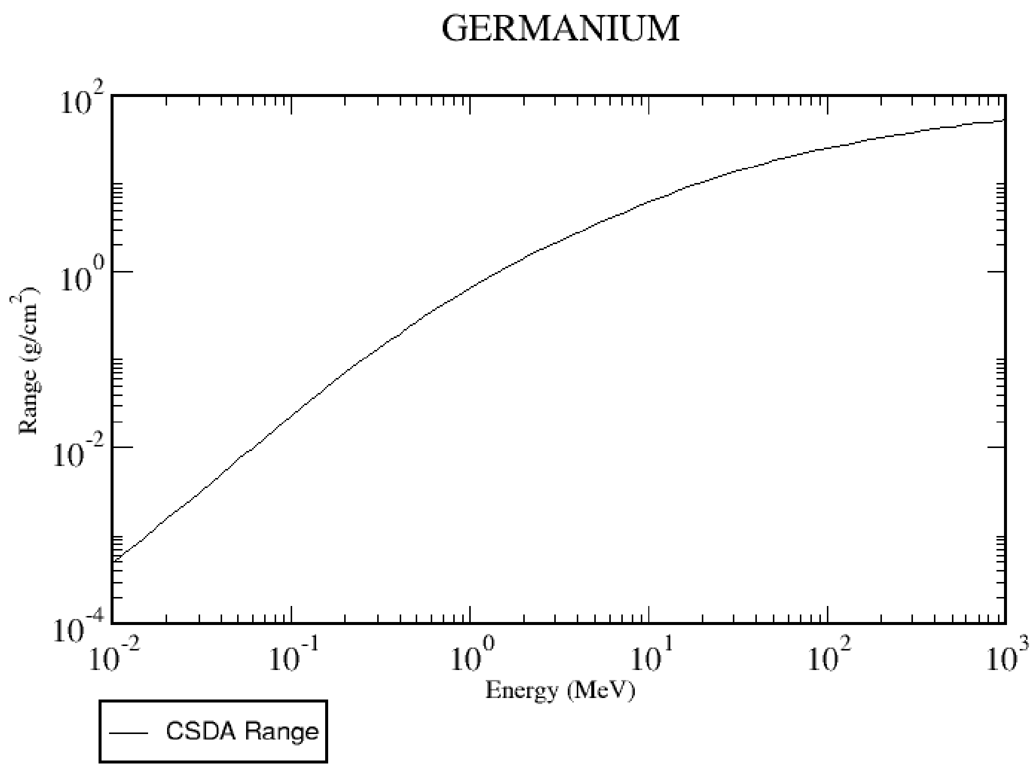


Figure 5.4 Beta penetration depth in Germanium

The density of Germanium is 5.323 g·cm^{-3}. The Ge semiconductor must be 0.563 mm thick to absorb the energy of the Krypton-85 radiation.

The ASTAR software [41] enables the calculation of the material stopping range of alpha radiation and is able to return the graph of the penetration depth of the alpha radiation for various materials. The Figure 5.5 shows the alpha penetration depth in Silicon and Figure 5.6 shows the alpha penetration depth in Germanium.

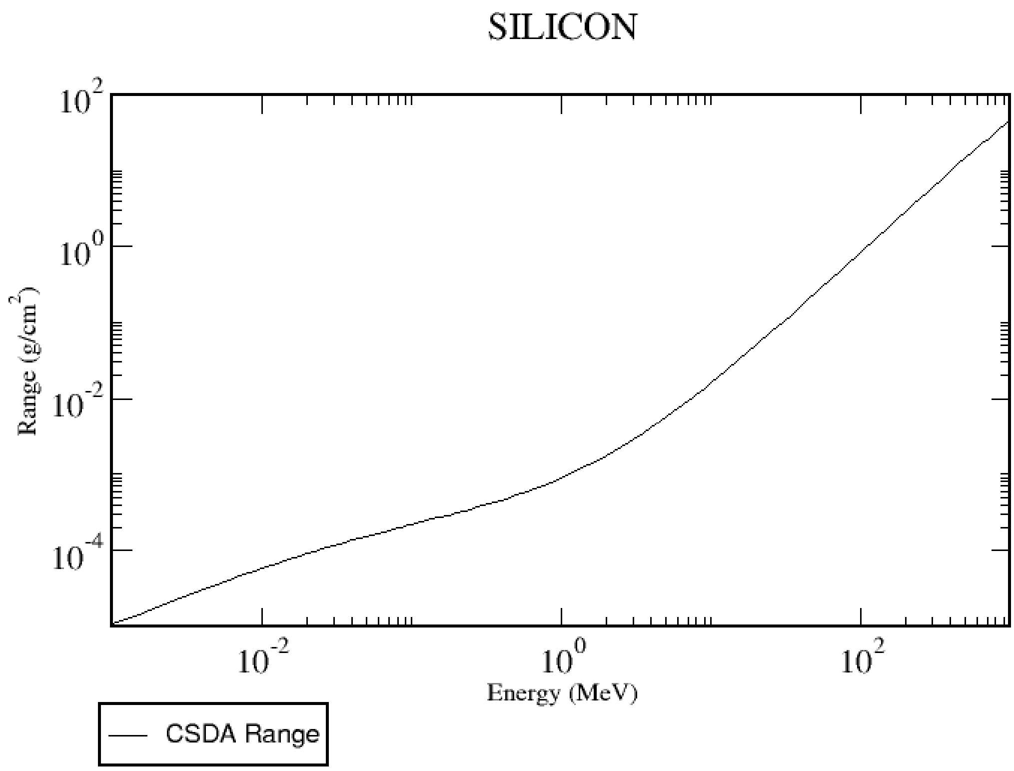


Figure 5.5 Alpha penetration depth in Silicon

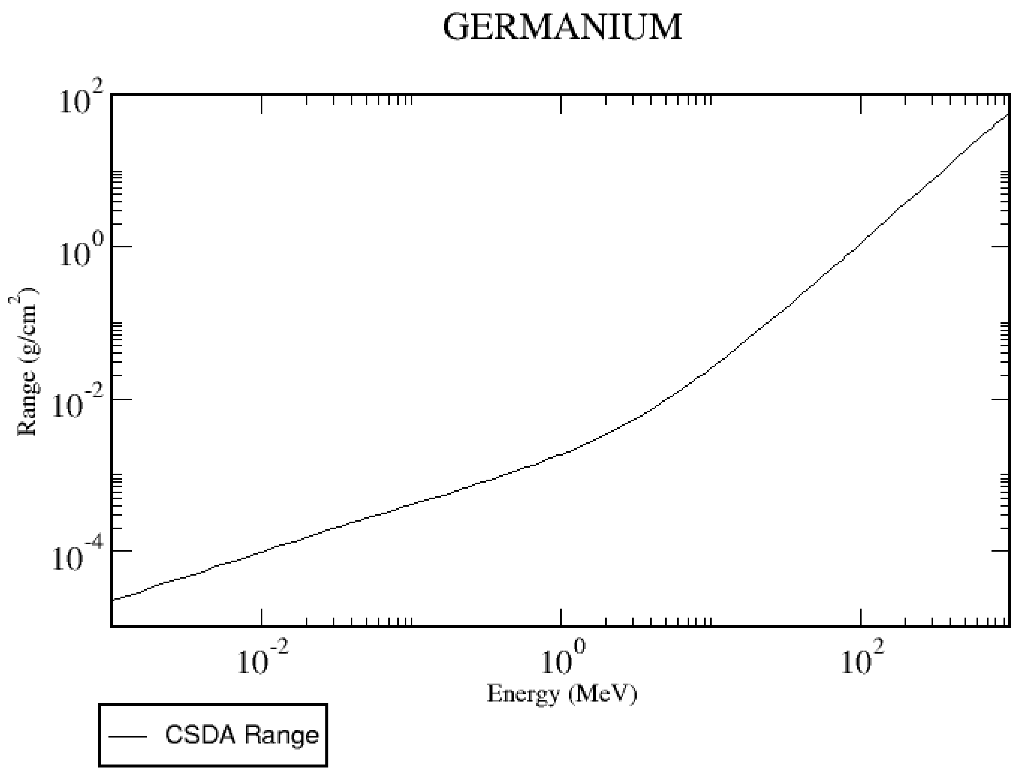


Figure 5.6 Alpha penetration depth in Germanium

Considering the energy of the Americium-241 alpha radiation of 5.638 MeV and the same densities as above, the alpha particle penetration depth in Silicon equals 28.875 µm. The alpha penetration depth in Germanium equals 12.634 µm.

5.3 Measurement and calculation evaluation

The calculated power output of Krypton-85 equals $4.02 \cdot 10^{-7}$ W and the power output of Americium-241 equals $9.03 \cdot 10^{-7}$ W. Not considering the efficiency values, the radiation power output itself is strongly insufficient to create a detected voltage on the electrodes of the used photovoltaic power cells. The monocrystalline power cell has power output of 2.5 W in comparison.

The calculated penetration depth of the beta radiation in Si semiconductor is 1.288 mm. The calculated alpha radiation penetration depth in Silicon equals 28.875 μm. Although the precise dimensions of the semiconductor depths are unknown, considering the calculated penetration depths, the monocrystalline solar cell used in the experiment had sufficient depth to capture the whole energy of the beta radiation. There is a chance the polycrystalline solar cell was robust enough as well. The rest of the semiconductors had insufficient depth to capture the higher energy electrons, that would pass right through them. Considering alpha radiations low penetrating abilities, it is safe to assume that all the cells captured the full energy of the radiation.

To produce the functional betavoltaic power cell, the low current cells are created. With the measured power outputs and achieving the current values in ranges of nanoamperes, it is possible to obtain up to single digits of volt values output voltage over the whole lifetime of the power cell. The semiconductors are custom made, grown in several layers connected in series to maximise the voltage output.

6 SUMMARY

This Bachelor's thesis introduces the reader to semiconductor nuclear cells and detectors. After describing every ionizing radiation and its properties, introducing the reader to semiconductor materials and their properties, the types of nuclear cells are explained, divided and discussed. Detector devices are described and divided into categories. A short historical review of radiation, semiconductors and nuclear cells is included.

In the next part of the thesis the betavoltaic nuclear cell is discussed. First it is introduced, its functionality mechanism is described and then its individual parts are explained and analysed. Krypton-85 and its properties are thoroughly discussed, since it is the material available for the practical part of the thesis, which consists of two measurement experiments.

The first measurement is performed to confirm the theoretical interaction between semiconductors and ionising radiation. As a radiation source, Krypton-85 and Americium-241 were utilised. Several measured objects did not react to the radiation exposure, but solar cells registered a slight drop of voltage while being exposed to the radiation.

The second measurement was carried out to confirm the findings of the first one and to repeat the measuring process with more accurate multimeter. The measurement disproves the findings of the first measurement, since the drop of voltage was only caused by blocking the sunlight from entering the measured solar cell. Both experiments are thoroughly described and documented.

In the last chapter of the Bachelor's thesis, the calculation is realised to confirm the measurement results. The total power radiated from the Krypton-85 is calculated to be equal to $4.02 \cdot 10^{-7}$ W. The radiated power from the Americium-241 equals $9.03 \cdot 10^{-7}$ W. The results confirmed the measurement results, since the solar cells had power output in units of Watts. The ionising radiation is too weak to cause any voltage change. The simulation using ESTAR and ASTAR software is made to calculate the penetrating abilities of the radiation in semiconductor materials. In Silicon, the beta radiation of Krypton-85 reaches as deep as 1.288 mm before running out of energy and the alpha radiation of Americium-241 penetrates 28.875 μm of the Si semiconductor. The Germanium semiconductor stops the radiation in half way the Si semiconductor does.

Although the measurement of the effects of ionizing radiation on semiconductor materials had negative result, the thesis unambiguously confirms that the interaction between ionising radiation and semiconductors takes place and that the topic carries a huge potential for the future applications.

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